

From THE DEPARTMENT OF DENTAL MEDICINE  
Karolinska Institutet, Stockholm, Sweden

# **EXTENSIVE TOOTH WEAR IN ADULTS; CLASSIFICATION AND PROSTHETIC TREATMENT**

Wedad Hammoudi



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# **Extensive tooth wear in adults; classification and prosthetic treatment**

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By

**Wedad Hammoudi**

*Principal Supervisor:*

**Associate Professor Jan-Ivan Smedberg**  
Karolinska Institutet  
Department of Dental Medicine  
Section of Oral Rehabilitation

*Co-supervisors:*

**Professor Mats Trulsson**  
Karolinska Institutet  
Department of Dental Medicine  
Section of Oral Rehabilitation

**Professor Peter Svensson**  
Aarhus University  
Department of Dentistry and Oral  
Health  
Section of Orofacial Pain and Jaw Functions

*Opponent:*

**Associate Professor Christel Larsson**  
Malmö University  
School of Dentistry  
Division of Prosthetic Dentistry

*Examination Board:*

**Professor Victoria Franke Stenport**  
University of Gothenburg  
Institute of Odontology  
Division of Prosthodontics/Dental Materials  
Science

**Professor emeritus Anders Ekfeldt**  
Oslo University  
Faculty of Dentistry  
Division of Prosthetic Dentistry and Oral  
Function

**Associate Professor Tulay Lindberg**  
Karolinska Institutet  
Department of Dental Medicine  
Division of Periodontology and Dental  
Prophylaxis Unit



*To my warm and warmly beloved family!*

My deepest gratitude to all the patients who participated in my project – for your patience, curiosity about your tooth wear, courage to try new devices, and willingness to devote the time required for different investigations, as well as for showing up so reliably for treatment and follow-up appointments, even during vacation time!

**THERE ARE NO INCURABLE DISEASES —  
ONLY THE LACK OF WILL.  
THERE ARE NO WORTHLESS HERBS —  
ONLY THE LACK OF KNOWLEDGE.**

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## LIST OF SCIENTIFIC PAPERS

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## **LIST OF ABBREVIATIONS**

AB	Awake bruxism
EMG	Electromyography
LD	Lithium disilicate
PSS	14-item Perceived Stress Scale
RCT	Randomized clinical trial
SB	Sleep bruxism
TW	Tooth wear
TWI	Tooth wear index
TZ	Translucent zirconia
USPHS	United States Public Health Service

## ABSTRACT

**Background:** Tooth wear (TW) is an insidious and cumulative multifactorial process that may comprise erosion, abrasion or attrition, and combinations thereof. These different processes are of chemical or physical origin and not microbiological. As our populations age, a certain degree of TW may be unavoidable and can be regarded as a normal physiological process, but when the form and function of the dentition are comprised, the condition can then be considered as pathological. The scientific literature in this area contains considerable information about the various risk factors for TW, but has failed so far to provide reliable procedures for the diagnosis, classification, and management of this condition.

**Aims:** The general aims of this thesis were as follows: 1) to apply the novel approach known as cluster analysis to the classification of phenotypic heterogeneity among patients with extensive TW; and 2) to evaluate the clinical relevance of this approach by comparing the clinical presentation of wear lesions and the long-term clinical performance and durability of two all-ceramic restorations in the clusters thus created.

**In Study I** unsupervised cluster analysis based on clinical findings, demographic and self-reported characteristics, and salivary and EMG measurements was used to differentiate between patients with extensive TW of different phenotypes. Data was obtained on 125 patient (17-65 (mean 43.1) years old, TW index > grade 2). The 34 variables of interest included demographic information; presumed risk factors for mechanical and chemical TW; a 14-item stress scale; salivary flow rates, pH and buffer capacity; jaw muscle activity during sleep (measured by single-channel EMG device); and the presence or absence of torus mandibularis. Cluster A (n=61) had a lower percentage of self-reported sleep bruxism (1.6%, vs 92.9%,  $p \leq 0.001$ ); self-reported awake bruxism (45.9%, vs 85.7%,  $p \leq 0.001$ ); and heavy exercisers (1.6% vs 21.4%,  $p = 0.001$ ); and a lower percentage of diseases that affect saliva (13.1% vs 47.6%,  $p \leq 0.001$ ) than cluster B (n=42). Otherwise, overlap was considerable.

**In Study II** a case control study was used to assess the distribution and morphological features of the wear lesions in clusters A and B (n=103; 22 participants in the first study were excluded due to incomplete data) The comparison was based on wear distribution, the presence or absence

of 10 morphological features associated with TW, and the number of teeth exhibiting each feature. Whereas cluster A demonstrated more wear in maxillary anterior teeth and mandibular molars than in the same opposing tooth groups ( $p < 0.001$ ,  $p < 0.007$  respectively), there were no such differences for cluster B. Cluster A was characterized by a higher prevalence of 4 morphological criteria for chemical TW and more teeth exhibiting one of these criteria; while cluster B had a higher prevalence of one mechanical criterion and more teeth demonstrating an additional mechanical criterion. Both intra- and inter-examiner reliability for the morphological assessments (as indicated by Cohen's kappa and the interclass correlation coefficient) were fair to excellent.

**Study III** describes a prospective, double-blind, randomized clinical trial that evaluated the performance and success rate of pressed lithium disilicate (LD) and translucent zirconia (TZ) crowns in patients with extensive TW. 62 patients (17 women, 45 men; mean age 44.8 (range 25-63) years) received a total of 362 LD and 351 TZ crowns. Modified USPHS criteria were used for clinical reevaluation on average 14, 31, 39, 54, 65 months after insertion. After as long as 6 years, the survival rate for both types of crowns was 99.7% ,with loss of retention by one LD crown after one year and loss of one TZ crown after 3 years due to tooth fracture at the cemento-enamel junction. The success rates were 98.6% for the LD and 99.1% for the TZ crowns. Already immediately after insertion, the color match was better with the LD than TZ crowns ( $P < 0.001$ ). Post-hoc analysis of clinical performance showed no significant differences between subjects with extensive TW exposed primarily to chemical or mechanical risk factors.

**Conclusions:** Patients with extensive TW can be clustered into at least two groups with different phenotypic characteristics, although with a large degree of overlap. Assessment of the clinical presentation of wear lesions indicated more chemical background for TW in the larger cluster and more mechanical background in the smaller cluster, a finding of potential clinical value. With the exception that TZ crowns were rated by a clinician as less esthetically appealing, there were no differences between the performance and success of these two types of all-ceramic materials used for rehabilitation. Regardless of the etiology of the TW, the key factor for long- term success of all-ceramic crowns in patients with extensive TW is probably the use of adhesively luted high-strength ceramic materials.

## POPULÄRVETENSKAPLIG SAMMANFATTNING

**Bakgrund:** Tandslitage (TS) är en smygande och kumulativ multifaktoriell process som kan omfatta erosion, abrasion eller attrition, och kombinationer därav. Dessa processer är av kemiskt eller mekaniskt ursprung och är inte mikrobiologiska. Med ökad ålder är ett visst TS oundvikligt och betraktas som fysiologisk, men när omfattningen är sådan att formen och funktionen är påverkade relativt individens ålder kan tillståndet betraktas som patologiskt. I litteraturen finns mycket kunskap redovisad om tandslitageots olika bakgrunds- och riskfaktorer, men det finns ingen tillförlitlig vetenskaplig metod för diagnostisering, klassificering eller behandling av TS.

**Syften:** Det generella syftet med denna avhandling var att tillämpa en ny klassificeringsmetod, så kallad klusteranalys, för att identifiera grupptypiska skillnader bland patienter med omfattande TS. Därefter skulle vi använda klusterutfallet för att se om metoden kan få en klinisk tillämpning genom bedömning av det kliniska utseendet av slitskadorna. Vi vill även jämföra det långsiktiga utfallet av två olika helkeramiska material i de framtagna klustren.

**Studie I** är en tvärsnittsstudie med avsikt att identifiera grupptyper hos patienter med omfattande TS via oövervakad klustermodell baserad på kliniska fynd, information om demografiska- och självrapporter, saliv och EMG mått. Data erhöles från 125 patienter i åldrarna 17-65 år (medelålder 43,1 år) med ett TS-index > grad 2. Totalt insamlades 34 variabler med demografisk information, riskfaktorer för mekanisk och kemisk TS, stress-skala, salivstatus i form av flödes hastigheter, pH och buffertkapacitet, käkmuskelaktivitet under sömn uppmätt med enkanals EMG-enhet och närvaron av benutväxter på underkäkens insida (tori). Analysen avslöjade två relativt distinkta kluster som också hade en stor grad av överlappning där 61 patienter tillhörde kluster A och 42 patienter tillhörde kluster B. Deltagarna i kluster B hade den högsta andelen självrapporterad sömnbruxism (A 1,6%, B 92,9%,  $p \leq 0,001$ ), självrapporterad dagbruxism (A 45,9%, B 85,7%,  $p \leq 0,001$ ), utövande av kraftsport (A 1,6%, B 21,4%,  $p = 0,001$ ) och högsta andelen sjukdomar som påverkar saliven (A 13,1%, B 47,6%,  $p < 0,001$ ).

**Studie II** är en fallkontrollstudie som bedömde de kliniska slitskadorna i de två grupptyperna som framkom i den första studien, med avseende på lokalisation och utseende. Eftersom 22 fall uteslöts i den första studien på grund av ofullständiga data angående stress-skalan, saliv- och/ eller EMG-mätningar, inkluderades 103 fall i denna studie. En jämförelse gjordes mellan de två klustren baserat på lokalisation av slitskadorna på tänderna, närvaro av 10 väldefinierade utseendemässiga TS-kriterier samt antalet tänder som uppfyllde varje kriterium. Intra- och inter-examinator-tillförlitlighet hos de 10 TS-kriterierna bestämdes av Cohens kappa- och intraklass korrelationskoefficient. Medan kluster A hade mer slitage i överkäkens framtänder och underkäkens molarer jämfört med samma tandgrupper i motstående käke ( $p < 0,001$ ,  $p < 0,007$  respektive), fanns det inga sådana skillnader i kluster B. Kluster A kännetecknades av högre förekomst av fyra kemiska utseendemässiga kriterier och högst antal tänder som påverkades av ett kemiskt kriterium. Kluster B hade däremot en högre förekomst av ett mekaniskt kriterium och ett högre antal tänder som påverkades av ett ytterligare mekaniskt kriterium. Både intra- och interexaminator-värden för de definierade TS-kriterierna var rimliga till utmärkta.

**Studie III** är en framåtblickande, dubbelblind, slumpmässig klinisk studie som utvärderade det långsiktiga utfallet av pressade litium-disilikat (LD) och translucent zirkonia (TZ) kronor hos patienter med omfattande TS. Totalt fick 62 patienter med omfattande TS (17 kvinnor, 45 män; medelålder 44,8 år; intervall 25-63 år) 713 kronor varav 362 i LD och 351 i TZ. Modifierade USPHS-kriterier användes för en klinisk utvärdering i genomsnitt 14, 31, 39, 54, och 65 månader efter utlämningen av kronorna. Efter en observationsperiod på upp till 6 år var överlevnaden för båda typerna av kronor 99,7% med en förlorad LD-krona efter ett år som ett resultat av förlust av retention, och en förlorad TZ-krona efter 3 år på grund av tandfraktur vid cement-emalj gränsen. Framgångsgraden var liknande för båda typerna av kronor: 98,6% för LD och 99,1% för TZ. Färgbedömningen var betydligt bättre för LD-kronor än för TZ-kronor ( $P < 0,001$ ). En post-hoc-analys av kliniskt utfall visade inga signifikanta skillnader mellan omfattande TS med kemiska eller mekaniska bakgrundsfaktorer.

**Slutsatser:** Patienter med omfattande TS kan indelas i minst två grupper med olika egenskaper, dock med stor överlappningsgrad. Bedömningen av det kliniska utseendet av slitskador indikerade en mer kemisk bakgrund

för TS i det större klustret (kluster A) och en mer mekanisk bakgrund i det mindre klustret (kluster B). Vidare kan vissa kliniska kriterier för tandslitage användas av tandvårdspersonal för att skilja mellan individer som tillhör en specifik TS-grupp med en kemisk eller mekanisk bakgrund. Inga kliniska skillnader hittades mellan de två typerna av helkeramiska material som användes för rehabilitering, förutom att TZ-kronor bedömdes av en blindad tandläkare som mindre estetiska än LD-kronor. Oberoende av den specifika TS bakgrunden är nyckelfaktorn för en långsiktig framgångsrik rehabilitering av patienter med omfattande TS troligen användningen av adhesiv-cementerade höghållfasta keramiska material. Slutligen vet vi att metoden och materialet använt i denna studie fungerar på patienter med mekaniska riskfaktorer, vilket tidigare varit ett olöst problem.





## INTRODUCTION

Dental wear develops through non-carious physiologic or pathologic processes and varies in etiology, extent and clinical presentation [1]. Since 1728, when Hunter published his observations about this condition, clinicians and researchers have been interested in the specific causes of different types of tooth wear (TW) [2]. In particular, as the incidence of caries in Western countries has decreased in recent decades, loss of tooth tissue due to wear has captured the attention of dental professionals in this part of the world [3]. Physiological dental wear can develop as mechanical and chemical challenges throughout life induce loss of tooth surface to varying extents [4]. In contrast, this process is considered pathological when the degree of surface loss is atypical for the age of the patient and causes pain or discomfort, or functional or esthetic problems [4].

TW is considered to be complex and multifactorial, arising from the interaction of various chemical, mechanical and biological factors (Fig.1). These factors include functional activity (chewing); parafunctional activities (e.g., bruxism); acidic diet; other aspects of a modern life-style (e.g., heavy sport exercise); conditions and diseases that expose the teeth to endogenous acids (e.g., eating disorders and gastric reflux); certain occupational environments; stress; dental structure; salivary dysfunctions (pH, buffering capacity, pellicle and biofilm); general health and certain medical drugs [5-7].



**Figure 1.** Fundamental mechanisms of tooth wear in adult patients

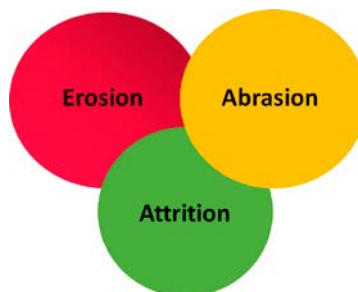
## The prevalence of TW

The prevalence of TW has been reported to range between 10-80% in children and 4-82% in adults [8]. Another report stated that the prevalence of extensive TW in adults ranges from about 3% at age 20 to 17% at age 70 [3]. The process of dental wear seems to have a strong correlation with age and is more common among men than women [9-11].

The apparent growing prevalence of this condition probably reflects, at least in part, differences in the samples examined and the approaches employed; lack of a uniform terminology with which to describe and classify TW; and the scarcity of international standardization [12]. Not to mention, the different grading systems (clinical indices) which might be more than 114 systems (including adaptations of already existing systems); yet, none of them is universally accepted [13]. These systems are based on a combination of etiology, the specific sites at which TW occurs and the degree of loss of tooth substance [12, 14]. Consequently, conclusions from prevalence studies should be interpreted with caution [15]. Furthermore, increased awareness among dental professionals together with a rising prevalence of the more severe stages of TW might help explain the growing number of publications in this area and enhanced concern among clinicians [3].

## Classification, etiology and presumed clinical characteristics of TW

The most common classification of TW was proposed by Pindborg and is based on three etiological classifications: attrition, erosion and abrasion [16](Fig. 2).



**Figure 2.** The bases of the most traditional classification of TW, proposed by Pindborg in 1970

Mechanical attrition is a result of tooth-to-tooth contact during mastication or parafunctional habits (day and sleep bruxism, biting the nails or other objects), without the involvement of foreign substances [17]. Clinically, incisal/occlusal wear, with similar degrees of wear on the occluding surfaces of opposing teeth involved in excursive jaw movements, is commonly attributed to attrition [18] (Fig.4). In the case of certain malocclusions, attrition may also involve buccal, lingual or interproximal surfaces [19].

Erosion involves chemical loss of tooth structure due to acids and/or chelation, without the involvement of bacteria [16, 20] (Fig. 3a and b). The acid in question may be endogenous or exogenous [21]. Endogenous erosion occurs when the teeth are exposed to hydrochloric acid produced by the stomach through gastric reflux, frequent vomiting (due to, e.g., anorexia, bulimia, alcoholism, gastrointestinal disorders, and pregnancy) or regurgitation in case of rumination [6, 22]. Exogenous erosion may be caused by acidic diets (e.g., carbonated soft drinks, fruit, fruit juices), medications, or occupational exposure (e.g., workers at battery, ammunition and galvanizing factories; wine testers; professional swimmers) [8]. Dental erosion can alter the original morphology of a tooth, flattening convex areas and resulting in the formation of occlusal concavities and an intact palatal border of enamel along the gingival margin [23, 24] (Fig.4).

Abrasion is defined as the loss of tooth substance via mechanical processes involving foreign objects, such as those utilized for oral hygiene [20]. Both *in vitro* and *in situ* exposure of enamel to acid renders it more vulnerable to toothbrush abrasion [19]. Abrasive lesions are typically located in cervical areas of the teeth and are usually wider than they are deep [25] (Fig.4).

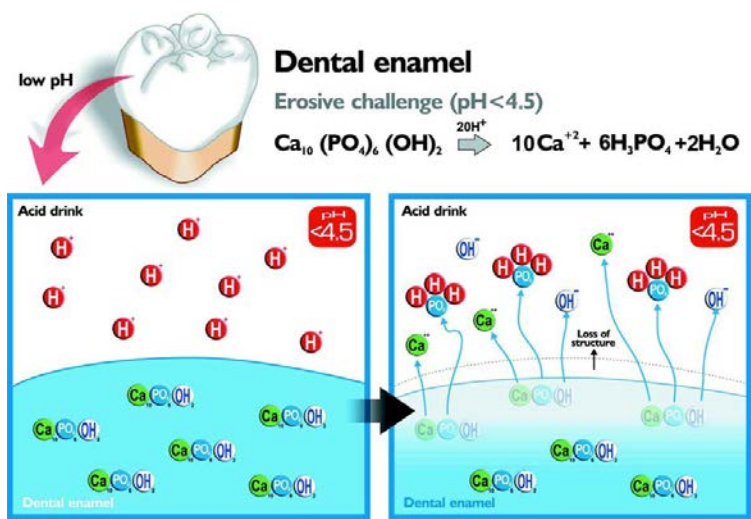


Figure 3a. Erosive demineralization of dental enamel (pH<4.5) [5]

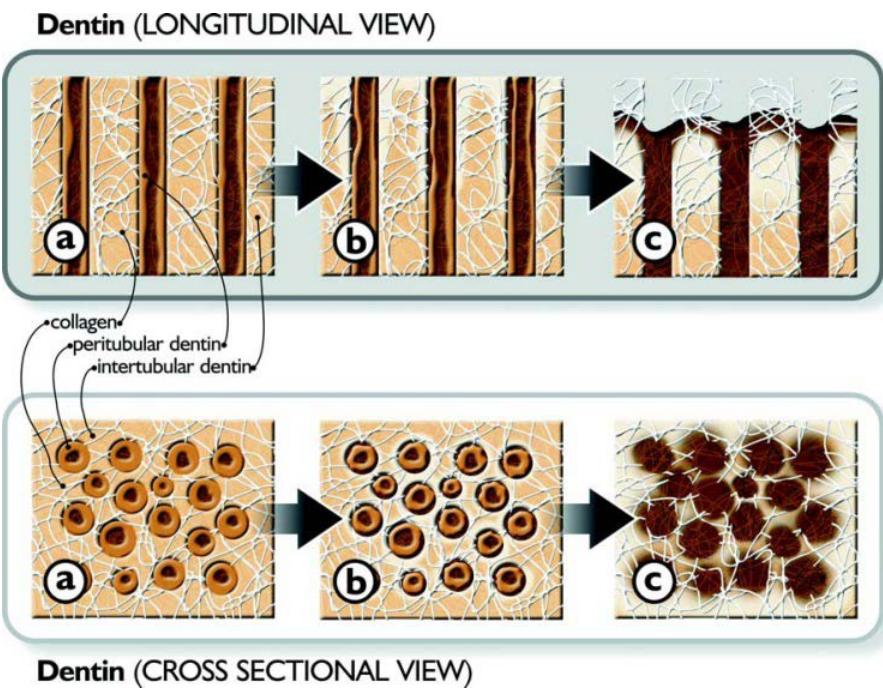
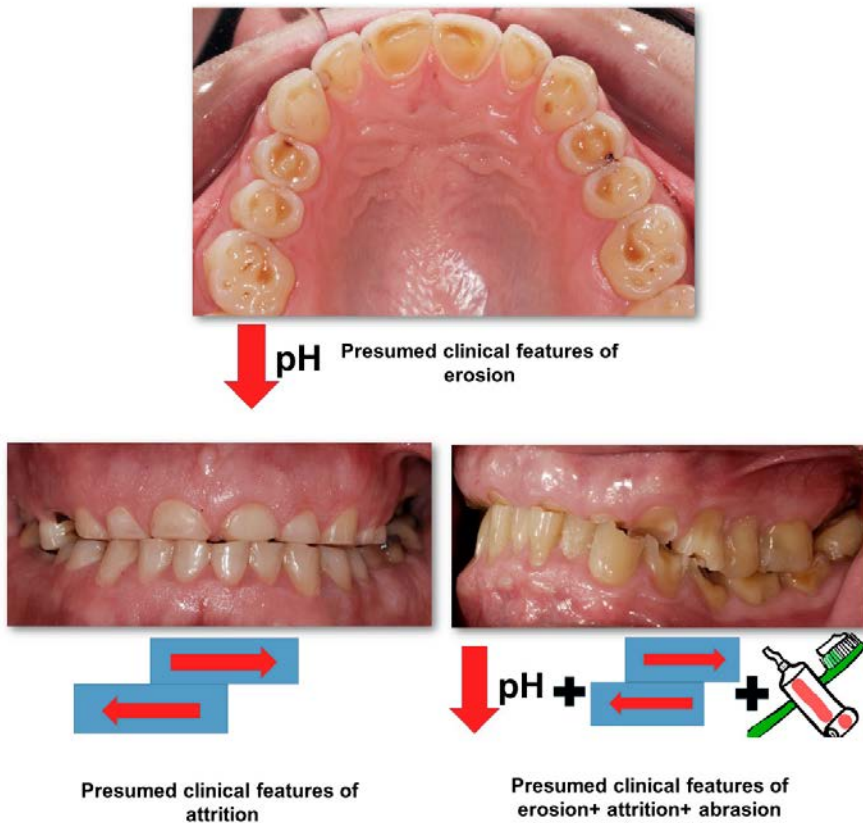


Figure 3b. Progressive erosive demineralization of dentin; a. healthy dentin, b. initial demineralization, c. the organic matrix becomes exposed [5]

Attrition, erosion and abrasion can occur independently, but more often these processes interact. Clinically, these processes occur to different extents in different individuals and at different points in time [6]. Much of the relevant evidence here comes from case reports or cross-sectional epidemiological studies, in both of which it is difficult to determine the impact of individual wear processes. In many cases and in order to highlight the involvement of an acidic component in TW, researchers use the relatively new term “erosive tooth wear”; defined as a “chemical-mechanical process resulting in a cumulative loss of hard dental tissue not caused by bacteria” [26].



**Figure 4.** Presumed clinical characteristics of dental erosion, attrition and abrasion

## The role of individual and interrelated factors

The individual and interconnected factors related to TW – including the properties of the such as saliva, composition and degree of hardness of the teeth, oral hygiene habits, tooth position and the anatomy of soft tissues – differ considerably between individuals [8, 27, 28]. Furthermore, both *in vitro* and *in situ* tooth brushing, tooth-to-tooth contact, tongue friction, and abrasion of surrounding soft tissues may produce mechanical stress on clinically eroded surfaces [28-30]. A recent genome-wide association study involving a subpopulation of the Northern Finland Birth Cohort 1966 (n=1,962) indicated that the gender and inter-individual variance in the severity of TW may have a genetic component [31].

## Salivary protection against TW

Saliva offers considerable protection against TW by diluting, clearing, neutralizing and buffering acids; lubricating; forming the protective acquired pellicle; and providing calcium, phosphate and fluoride, thereby reducing demineralization and enhancing remineralisation [32, 33]. It is important to remember that while saliva can attenuate TW, it cannot prevent this process. Previous investigators have drawn conflicting conclusions concerning the use of salivary parameters such as flow rate, pH and buffer capacity as predictors for dental wear [34].

Moreover, it has been proposed that the pellicle acts as selective barrier that prevents direct contact between acids and the surface of teeth, thereby reducing the dissolution of hydroxyapatite [5]. Although protection of the tooth surface by the pellicle has been demonstrated in several studies, the role played by the pellicle importance in connection with dental erosion is still poorly understood [33]. Some 130 different proteins in the saliva and dental pellicle have been identified as potential biological markers for TW, but their role in the development of TW remains unclear [35, 36]. Interestingly, many patients with dry mouths, who often complain of dentin hypersensitivity and therefore avoid acidic foods, show no signs of TW [37].

## **The potential effects of bruxism on TW are controversial**

In 2013, an international group of experts proposed the following definition: “Bruxism is a repetitive jaw-muscle activity characterized by clenching or grinding of the teeth and/or by bracing or thrusting of the mandible. Bruxism has two distinct circadian manifestations: it can occur during sleep (indicated as sleep bruxism) or during wakefulness (indicated as awake bruxism)” [38]. In an updated consensus in 2018, awake bruxism (AB) and sleep bruxism (SB) were considered to involve different masticatory muscle activities or behaviors [39]. Furthermore, this later consensus stated that bruxism should not be considered a disorder in otherwise healthy individuals, but rather a behavior that can result in certain beneficial or detrimental clinical consequences [39]. In some individuals, bruxism may even have positive consequences; e.g. being the ending episode of respiratory arousals prevents the collapse or restore the patency of the upper airway whilst asleep [40, 41], enhancing salivation in case of gastro-esophageal reflux and thereby reducing the risk for chemical TW [42]. Conversely, when the consequences are negative (e.g., pain in the masticatory system), bruxism may be considered pathological [39].

SB has been more extensively studied than AB. In general, there are few reports on the prevalence of bruxism among adult populations and the results obtained vary widely due to poor methodology and lack of distinction between different types of bruxism [43]. In Sweden, Denmark and Israel, the average overall prevalence of AB was found to be two-fold higher than that of SB [44-46]. In contrast, 5 % of a Dutch population of adults were recently found to demonstrate AB, while the corresponding prevalence of SB was 16.5%, i.e., more than three times higher [47]. In this same study women reported experiencing both types of bruxism more often than men.

The clinical signs of bruxism include mechanical TW, hypertrophy of the masseter muscle, hyperkeratosis of the cheek mucosa (linea alba), impressions of the teeth on the tongue and/or lips, fractured teeth, fractures and/or failures of restorations/implants not caused by problems with these devices themselves, torus and exostosis [6, 48]. Although questionnaires can be administered relatively easily to large numbers of individuals, no consensus has yet been reached concerning which questions should be used to confirm the presence of AB/SB [47].



Furthermore, although several diagnostic measurements (e.g., electromyographic and polysomnographic recordings) are available, it remains unclear for how long masticatory muscle activity should be measured and, in particular, how this activity is related to bruxism [39]. Indeed, the potential effects of bruxism on dentition, soft tissues and bone are quite controversial [6]. Likewise, the relationship between the extent of bruxism and severity of TW has been questioned [49, 50].

## Diagnosis and prevention of TW

When diagnosing TW, visual identification and evaluation of clinical features are essential [51]. Monitoring the progression of this condition, a key aspect of patient management both prior to and after restorative rehabilitation, can be achieved with high-quality clinical photographs, periodic use of casts and comparison to a silicone index based on the initial evaluation [20]. In the future, more reliable digital assessment of tooth wear will certainly become available.

The approaches to prevention of TW that are presently recommended include appropriate diagnosis of the lesions; identification of the likely causes; grading the severity of wear and risk assessment; and appropriate advice concerning the progress of the individual's disease and prevention [37, 51]. These approaches should always take into consideration the patient's medical history, life-style and environment.

Although no longitudinal studies concerning effects of fluoride have yet appeared, all kinds of fluoride has been shown to reduce TW, both *in vitro* and *in vivo* [37]. However, this protective effect might be limited in an aggressive acidic environment (e.g. reflux disease and eating disorders) as the fluoride ions get depleted rapidly [52]. Similarly, delaying tooth-brushing after an acid challenge seems to have no significant advantage since full re-mineralization of eroded tissue is difficult to attain, even after 2-4 h of waiting before brushing [37]. It is the acid challenge that should be seen as the risk factor rather than brushing after an acid challenge.



## **To restore or not to restore**

Irrespective of the severity of TW, prior to initiating a restorative cycle, appropriate preventive measures, counselling and monitoring are necessary [53, 54]. However, many patients seek treatment only when their TW is well advanced [55], so that a need to restore or rehabilitate a worn dentition often exists at the time of the first dental visit. Clinical judgment regarding the option to restore or not should consider the risks and benefits of doing so in each patient. It has been suggested that “the key roles in restoring the worn dentition are to bond, fill and polish more so than drill and fill” [7].

The recommendation formulated in connection with a recent European consensus meeting was that management of severe TW should be based on both the severity of the condition and the patient’s wishes [4]. It should always be remembered that the outcome of prosthetic management of extensive TW is not certain, due to the limited amount of tooth substance remaining, as well as the fact that any restoration may be ineffective in the face of repeated chemical insults and/or excessive mechanical loading [56].

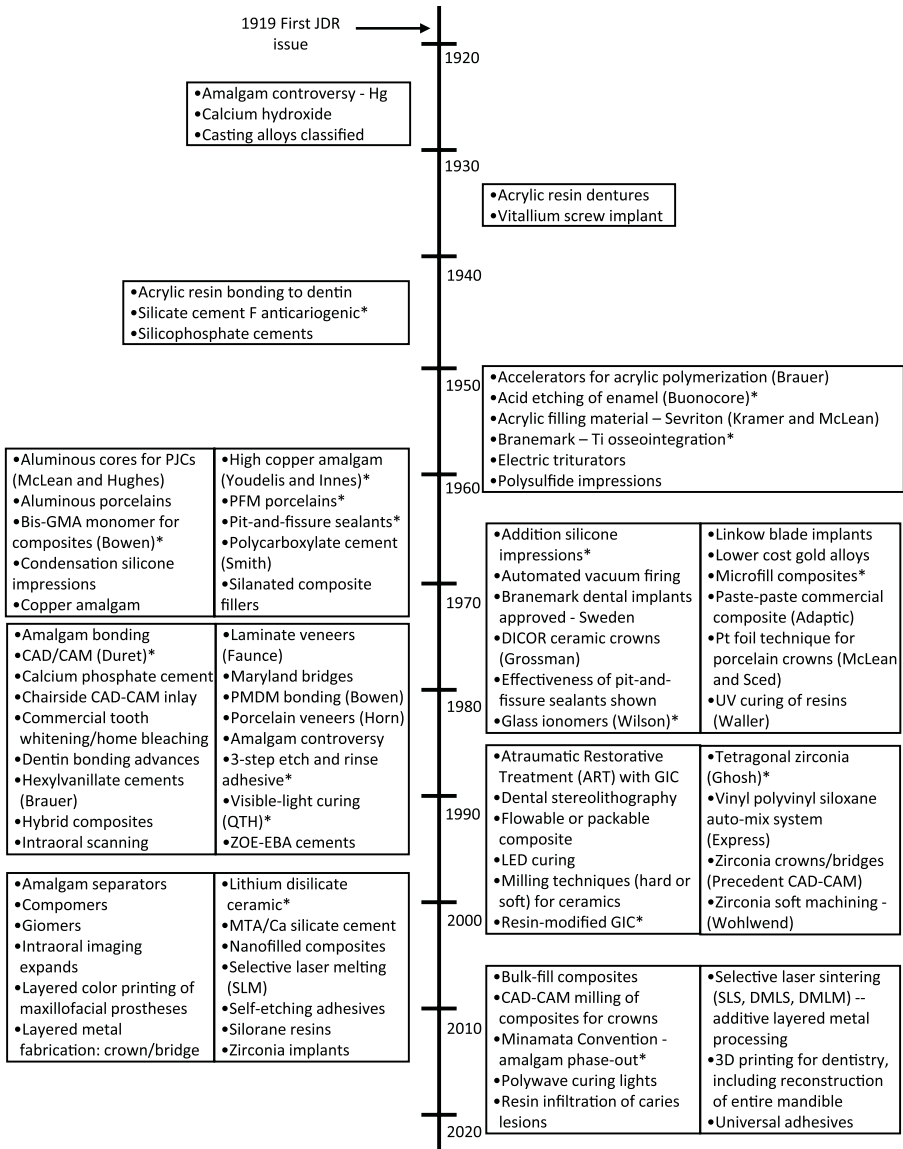
It has been reported that restoration of worn dentition with composites used to be associated with a high incidence of fractures and increased long-term costs due to the continuous need for repair and review [57, 58]. Thus, full-coverage crowns remain an important option in connection with the treatment of TW, especially in cases where this condition is extensive and composites have failed repeatedly [57]. It has been proposed that if fixed dental prosthesis is planned, this should involve minimal extension and with this approach splinting with additional abutment in order to compensate a short or poorly retentive primary abutment is contraindicated [14].

## **Types of restorative material**

Almost all studies on the durability of restorative materials have been performed in the laboratory and extrapolation of such findings to the extremely variable conditions in patients is extremely difficult [59]. Overall, in cases involving high load, metal or metal-ceramic restoration

appear to be safest choice [60], but the recently increasing esthetic demands of patients are met better by dental ceramics. The use of monolithic lithium-disilicate, a modern and highly attractive adhesive dental ceramic, has several advantages over conventional multilayer restorations [61]. Similarly, translucent zirconia, introduced around 2011, claimed to combine both good esthetic and load bearing capacity. The major clinical advantage of monolithic restorations is their reduced thickness, which requires less removal of tooth substance [62]. Such restoration can also offer a good approach to avoiding chip-off fractures [63, 64].

Actually, as shown in Figure 5, during the last century the development of dental materials has been revolutionary [63]. Facilitated by the rapid improvements in dental adhesive materials, the most pronounced advances have been esthetic, as reflected in by the replacement of dental amalgam with composites and of all-metal and porcelain-fused-to-metal restorations with reinforced dental ceramics [63]. Indeed, there are many untested materials in the market, many more than needed, and some even disappear very quickly, a situation that certainly complicates long-term clinical trials on dental restorative materials and adhesives.



**Figure 5.** Timeline of milestones in the development of dental materials (1919–2018). The developments/discoveries that occurred during each decade are displayed in alphabetical order, with those that had the highest clinical impact being indicated with an asterisk. Bis-GMA, bisphenol A glycidyl methacrylate; CAD, computer-aided design; CAM, computer-aided manufacturing; DMLM, direct metal laser melting; DMLS, direct metal laser sintering; GIC, glass ionomer cement; LED, light-emitting diode; MTA/Ca, mineral trioxide aggregate; PFM, porcelain fused-to-metal; PJC, porcelain-jacket crown; PMDM, pyromellitic dimethacrylate; QTH, quartz tungsten halogen; SLS, selective laser sintering; UV, ultraviolet; ZOE-EBA, zinc oxide eugenol–ethoxybenzoic acid [63]

## **Unanswered questions and the gaps in knowledge that the present project attempted to fill**

Many questions concerning the etiology of TW and relationships between risk factors remain unanswered [14]. Moreover, the scientific literature contains numerous proposals and guidelines for the classification and systematic diagnosis and/or management of TW. However, most of these only summarize existing research, with no evaluation of diagnostic accuracy or feasibility [65-67]. Nonetheless, clinicians continue to provide extremely expensive and extensive therapies without evidence of beneficial long-term outcomes.

Furthermore, the absence of documented outcomes regarding the rehabilitating of worn dentition is striking and existing recommendations are based on clinical experience and the opinions of respected authorities, rather than scientifically rigorous RCTs [14]. The many explanations for this include difficulties in defining the study group and in recruiting a sufficient number of patients, as well as the challenging nature of restorative treatment, with its relatively high risk of failure. In addition, the position within the dental arch of the teeth that show wear, the type of occlusal relationship and the quality of the remaining tooth tissue all complicate the standardization of the treatment.

The lack of a reliable diagnostic approach, including standardized classification, makes it difficult to study TW and until this changes, treatment cannot be based on evidence and will continue to be debatable. A new analytical approach for classification of TW which takes into consideration the multifactorial nature of this condition would be of considerable value in this context. The current project attempts to improve the classification and evaluation of prosthetic rehabilitation of extensively worn dentition.

## **Cluster analysis; why and how?**

For decades, researchers in various fields of medicine have explored numerous approaches to analysing data, such as grouping objects on the basis of their characteristics, so-called cluster analysis [68-70]. The primary approach to cluster analysis involves grouping individuals on the basis of a predetermined criterion, often the similarity in their responses to several factors. This approach is particularly useful when researchers are faced with a large number of observations that are difficult to interpret unless classified into manageable groups [71] or when studying a multifactorial process/disease, like TW.

With cluster analysis objects are grouped into subsets that have meaning within the context of a particular problem, thereby providing a useful representation of the population being sampled. Unlike traditional classification, clustering does not rely on predefined classes, i.e., no prior information concerning the group or cluster membership for any of the objects is required. This approach can reveal previously undiscovered relationships in a complex set of data.

For example, one research group was attempting to explain the phenotypic heterogeneity among patients with periodontitis on the basis of patterns of bone loss and microbiological data [72]. They found that most of these patients could be grouped into 3 clusters with distinct phenotypic characteristics: one group consisted of young individuals with a tendency for localized bone loss and sub-gingival *A. actinomyces*, while the other two groups differed mainly with respect to disease severity and smoking habits. Such results could provide a basis for disease classification and planning of treatment.

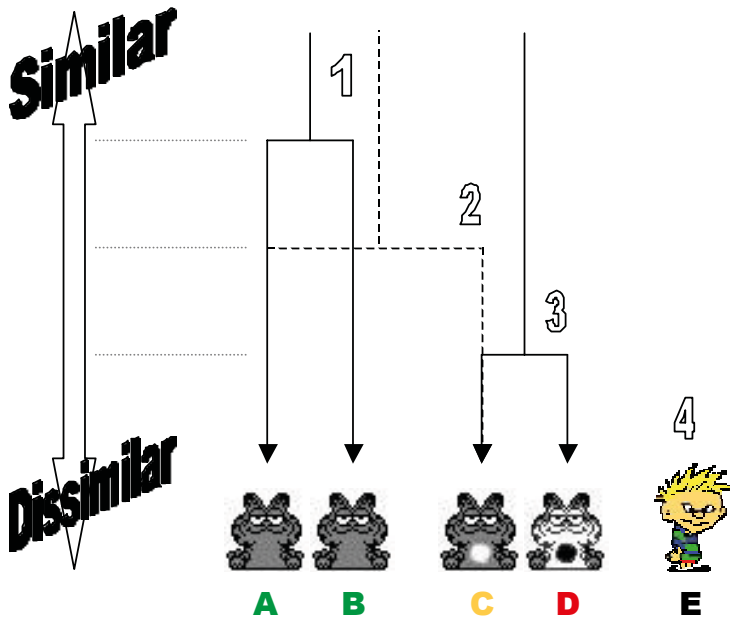
The basic principles behind the formation of clusters is illustrated below in Figure 6. Clustering of these 5 animals (A, B, C, D and E from left to right) on the basis of their physical characteristics (color, number of legs, number of eyes, etc.) would involve four stages:

*Stage 1.* Each animal begins as its own cluster. The algorithm first identifies the two animals who are most similar (in this case, A and B look identical) and combine these to form the nucleus of a larger cluster.

*Stage 2.* The animal next entered into this larger cluster is the one exhibiting the highest similarity to *either* A or B. In this case, C is similar in all respects except for its white belly.

*Stage 3.* The next animal to be included in the cluster is the one most similar to A, B or C, i.e. D, whose color is completely different.

*Stage 4.* Such a series of selections can introduce a great deal of dissimilarity into a cluster. E is a human, but still possesses certain physical characteristics that are similar to those of A, B, C or D. Thus, E can either be placed in the same cluster or form the nucleus of a new cluster.



**Figure 6.** Different stages of clustering for analysis  
(Modified from <http://www.discoveringstatistics.com/docs/cluster.pdf>)

The algorithm used at this different stages can be thought of as a kind of “artificial intelligence” that performs a job that might be virtually impossible for you to do, especially in the case of a complex dataset. The overall analysis comprises a number of steps: precise formulation of the problem, selection of a distance measure, selection of a proper clustering procedure, deciding the number of clusters, interpreting the profile of the clusters and, finally, evaluation of the validity of the clustering obtained. The variables selected should take the findings of past research into consideration. Likewise, to have a theory, tested hypotheses, and the judgment of the researcher are important aspects. Although many clustering procedures are employed, hierarchical, non-hierarchical and two-step procedures are the most common. The choice of procedure depends on several factors, such as the size of the dataset and nature of the variables (categorical or continuous) of interest [72, 73].

## **AIMS OF THE PRESENT THESIS, INCLUDING THE HYPOTHESIS TO BE TESTED**

### **General aim**

The general aim of the present thesis was to utilize cluster analysis to achieve a novel classification of patients with extensive TW based on their phenotypic heterogeneity. Thereafter, the clusters thus generated were studied and related testing interventions were evaluated in a randomized controlled trial.

### **General Hypothesis**

With cluster analysis, individuals with several chemical and mechanical risk factors for TW can be divided into relatively well-defined groups on the basis of the similarities and differences in their characteristics.

### **Specific aims and hypothesis**

#### **Study I**

This study explored a new approach to the identification of phenotypes of patients with extensive TW employing unsupervised clustering based on demographic and self-report information in combination with clinical, salivary and electromyographic findings. We hypothesised that different phenotypes among patients with extensive TW can be identified in this manner.

#### **Study II**

The first aim here was to evaluate the morphology and distribution of wear lesions in the two groups of patients with TW identified in Study I. Our hypothesis was that these characteristics of TW in these two groups would not differ. An additional goal was to establish tentative criteria for a diagnosis of TW and to assess the intra- and inter-examiner reliability of these criteria.

### **Study III**

This prospective, double-blind, randomized clinical trial was designed to compare the long-term clinical performance and durability of crowns composed of two all-ceramic materials – i.e., pressed lithium disilicate (IPS e.max-Press, Ivoclar Vivadent) and translucent zirconia CAD/CAM (BruxZir 3Y-TZP zirconia, Glidewell Laboratories)—in connection with rehabilitation of patients with extensive TW. The null hypothesis was that there would be no difference between those two types of all-ceramic crown materials.

Moreover, it was decided post-hoc to compare the outcomes of crown therapy for the two clusters established previously, since such comparison is important from a prosthodontic point of view. The hypothesis in this case was that with regards to prosthetic rehabilitation with all-ceramic crowns, the long-term clinical outcome for patients with mechanical risk factors is worse than for those with chemical risk factors.



## MATERIALS AND METHODOLOGICAL APPROACH

### Patients

In these studies, all subjects received both oral and written information about the study before providing written consent to participate. The same inclusion and exclusion criteria were applied in all cases. Figure 7 presents a flowchart illustrating the recruitment of patients.

### Study I

Of the referrals received by the Department of Prosthetic Dentistry at Folk tandvården, St Erik's Hospital and Eastmaninstitutet from 2012-2017, 5000 involving a variety of prosthetic problems were screened. Of the 343 patients with TW initially selected by one of the investigators (WH) and asked to participate, 44 refused and 11 did not respond, despite receiving two reminders. The remaining 288 patients who agreed to participate were assessed further on the basis of the criteria for inclusion and the final study population consisted of 125 patients.

Those criteria for inclusion were as follows:

- An age of 17-65 years
- At least 10 teeth remaining in the upper and lower arches
- TW > grade 2 for any surface on at least four teeth in the same arch, as assessed by the tooth wear index (TWI) formulated by Smith and Knights (TWI) [74] (Tab.1)
- A low risk for caries
- Good oral hygiene and a periodontal pocket depth  $\leq 4$  mm, with no bleeding when probed

The following criteria for exclusion were applied:

- Fixed and removable partial dentures
- Gross malocclusion (severe Angel's Class II or III)
- Mineralisation disorders
- Pain upon palpation of the temporomandibular joint
- Widespread facial pain
- Neurological, psychiatric or sleep disorders
- Pacemaker

Score	Surface	Criteria
0	B/L/O/I	No loss of enamel surface characteristics
	C	No loss of contour
1	B/L/O/I	Loss of enamel surface characteristics
	C	Minimal loss of contour
2	B/L/O	Loss of enamel exposing dentine for less than one third of surface
	I	Loss of enamel just exposing dentine
	C	Defect less than 1mm deep
3	B/L/O	Loss of enamel exposing dentine for more than one third of surface
	I	Loss of enamel and substantial loss of dentine
	C	Defect less than 1-2mm deep
4	B/L/O	Complete enamel loss-pulp exposure-secondary dentine exposure
	I	Pulp exposure or exposure of secondary dentine
	C	Defect more than 2mm deep-pulp exposure-secondary dentine exposure

**Table 1.** The tooth wear index devised by Smith and Knight

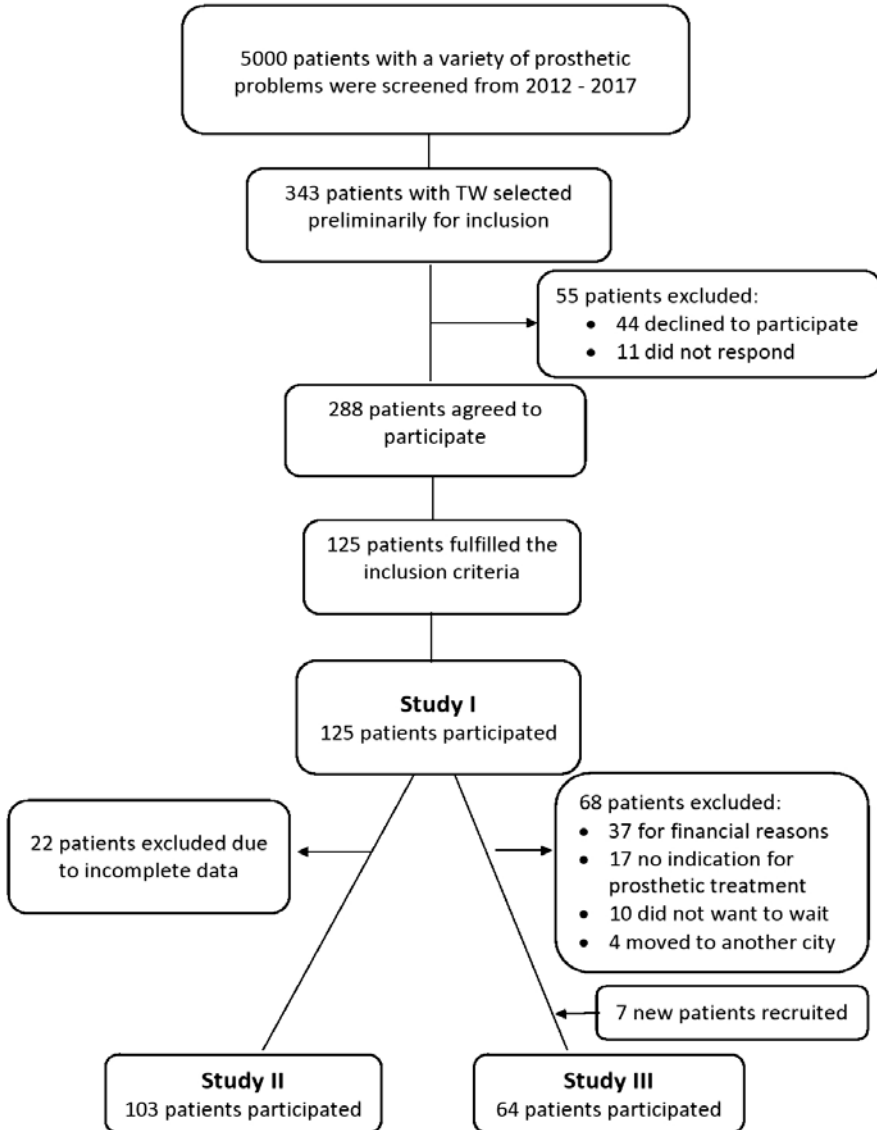
## Study II

In this case the study population consisted of 103 patients who had already been clustered in the first study into two relatively distinct groups: 61 in cluster A and 42 in cluster B. This cluster assignment was based primarily on several presumed mechanical risk factors and diseases that affect saliva. The patients allocated to cluster B had, on average, more presumed mechanical risk factors as sleep- and awake bruxism self-reports, heavy sports exercises; as well as a higher incidence of diseases that affect the saliva. Notably, the patients in these two clusters had many other presumed risk factors for mechanical and chemical TW in common.

## Study III

This study included 132 patients recruited from 2012- 2018, of whom 125 had participated in Studies I and II and the remainder were newly recruited (Fig.7). This single-center, double-blind randomized controlled trial was conducted between 2012 and 2018. For the following reasons,

68 patients were excluded: economic grounds (n= 37); no indication for prosthetic treatment (n=17); difficulties waiting, which led to their receiving treatment from another dentist (n=10); or moving to another city (n=4). Consequently, 64 patients underwent prosthetic rehabilitation.



**Figure 7.** Recruitment of the patients involved in Studies I-III

## General methodological approaches

All three studies were performed at Folktandvården, St Erik's Hospital and Eastmaninstitutet, Department of Prosthetic Dentistry, Stockholm, Sweden. Upon enrollment, all patients were examined and interviewed by the same investigator (WH). They completed a similar comprehensive battery of questions, clinical assessments and measurements, as described below.

### Demographic characteristics and clinical examination of the patients

The age; gender; body-mass index; medical history; number of maxillary and mandibular teeth; number of maxillary and mandibular teeth with TW > grade 2; dental caries; number, type and quality of restorations, as well as the presence of torus mandibularis were recorded for all participants. Extra and intra-oral photographs were taken and study casts made for all our subjects.

### Self-reported information

Possible risk factors for TW were evaluated using two standardized questionnaires based on our own clinical experience and literature reviews [6, 7, 75, 76], along with personal interviews. Some participants had only a single risk factor, while others had several. Thereafter, the responses were divided by the same interviewer into three groups with combinations of individual risk factors sufficient to be considered causes in the following manner (Tab.2):

- Presumed risk factors for chemical TW, including a history of gastric reflux and conditions involving intrinsic acids; previous dietary alterations due to, e.g., bulimia or anorexia nervosa, weight loss and gain; an acidic diet ( $\geq 4$  times/week); frequent alcohol intake ( $\geq 4$  times/week); wine testers, club and restaurant workers; and acidic medication
- Presumed risk factors for mechanical TW, including self-reported sleep or awake bruxism; nail, lip, cheek and pencil biting; working in a dusty environment; heavy labour (e.g., builders, carpentors, truck drivers); heavy exercise (body-builders); and use of snuff
- Presumed factors that affect saliva, including diseases like asthma, depression, diabetes melitus, hypertension; drugs that affect salivary protection; and overly much involvement in sports ( $> 3$  times/week)

Section	
<b>A</b>	Presumed risk factors for chemical TW
	History of gastric reflux and conditions involving intrinsic acids Previous conditions of dietary alterations (Bulimia nervosa and anorexia nervosa, weight loss and gain) Acidic diet Frequent alcohol intake Wine testers/club- and restaurant workers Acidic medication
<b>B</b>	Presumed risk factors for mechanical TW
	Self-reported sleep bruxism Self-reported awake bruxism Nail biting, lip or cheek biting, pencil biting, etc. Working in a dusty environment Heavy labour (Builders, carpenters, truck drivers, etc.) Heavy sport exercisers (body builders) Snuff
<b>C</b>	Presumed factors affecting saliva
	Diseases like asthma, depression, diabetes mellitus, hypertension Drugs affecting salivary protection Sports enthusiast (>3 times/week)

**Table 2.** Collected presumed risk factors for chemical and mechanical tooth wear and presumed factors affecting saliva in study participants

### Appraisal of stress

The 14-item Perceived Stress Scale (PSS) [77] was completed by all participants in order to evaluate stressful feelings and thoughts they experienced during the past month. Items 4, 5, 6, 7, 9, 10 and 13 were considered to be stated in positive terms. By reversing the scores on these items (i.e., a score of 0 became 4, 1 = 3, 2 = 2, 3 = 1 and 4 = 0) and then summing the scores for all 14 items, a PSS score was obtained for each participant.

### **Determination of salivary flow rate, pH and buffer capacity**

Salivary flow rate (both unstimulated and stimulated), pH and buffer capacity were determined between 8 AM and noon. The participants were required to refrain from drinking, eating, using tobacco and brushing their teeth for at least one hour prior to the collection of saliva.

### **Measurement of jaw muscle activity during sleep**

A portable single-channel EMG device (GrindeCare Measure3, Medotek A/S, Herlev, Denmark) was used to record the activity of the anterior temporalis muscle during sleep [76, 78]. The participants received thorough and careful instructions concerning how to use this device in their own home during sleep and a minimum of 4 nights' of error-free recordings was obtained for each subject. The parameters provided by this device included the number of nights recorded; EMG intensity; EMG grinds, episodes and bursts (total numbers and numbers/hour); and the average duration of EMG bursts.

### **Preventive measures**

Prudent preventive measures were offered to all participants. Follow-up monitoring involving the use of study casts and clinical photographs, as well as direct composite resin were offered to all of the participants who did not undergo prosthetic treatment. Composite restorations were carried out by general dental practitioners.

## **Special methodological approaches**

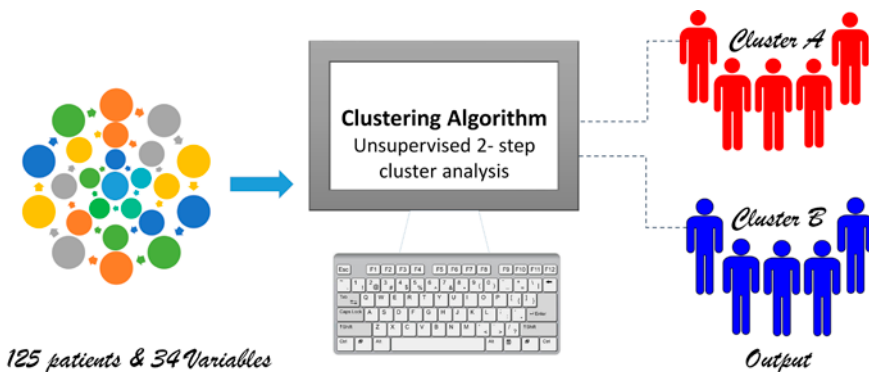
### **Cluster analysis (Study I)**

Since data on both numerical and categorical variables were collected, two-step cluster analysis was considered suitable here. A total of 34 variables were considered (Fig. 8), but the use of so many to identify a cluster model might reduce the quality of the resulting clusters. For this reason, variable selection/reduction was crucial and our strategy for this was based on several factors:

- Choosing variables more strongly associated with the outcome of interest on the basis of previous knowledge.
- Application of binary logistic regression to identify the most relevant numerical variables.

- Exclusion of variables that impaired the quality of the cluster model, as well as certain variables that occurred infrequently.
- Aggregation of some variables by combining two self-reported symptoms for sleep bruxism as well as two self-reported symptoms for awake bruxism.






In order to determine the appropriate number of clusters that should be generated, “unsupervised” 2-step cluster analysis was utilized and the final cluster model included 16 different variables and generated two clusters of patients.



**Figure 8.** The clustering analysis

### **Clinical presentation of TW lesions (Study II)**

A study manual consisting of 6 clinical photographs was created as a guide for the identification of the 10 morphological features of TW (Fig. 9); most commonly used to identify this condition, as indicated by a comprehensive review of the literature [2, 5, 7, 19, 79] and our own clinical experience. Two observers (WH and J-I S) compared the actual TW lesions with those illustrated in the study manual. After reaching agreement, they registered the presence of the morphological features present, as well as the number of teeth exhibiting each feature for each patient. Later, intra- and inter-observer reliability were assessed by allowing both observers to assess the teeth of 41 patients selected randomly in the same manner.

<p>1. Thin and irregular incisal enamel with increased translucency (13-23)</p>	
<p>2. More extensive wear on the upper than lower anterior teeth (all surfaces of 13-23)</p>	
<p>3. Concavities and cupping on the occlusal surfaces of premolars and molars</p> <p>4. Loss of convexities on the palatal side of maxillary teeth (17-27)</p> <p>5. Intact palatal border of enamel along the gingival margin of maxillary teeth (17-27)</p> <p>6. Margins of existing restorations higher than the structure of surrounding (premolars and molars)</p>	
<p>7. Cervical/buccal lesions that are wider than they are deep (all teeth)</p>	
<p>8. Similar degrees of plain occlusal/incisal wear lesions in both arches (all teeth)</p> <p>9. Wear between two or more moving/functional surfaces with matching facets (all teeth)</p>	





**Figure 9.** The study manual illustrating the sites of and morphological criteria for pathological dental wear

### **Radiographic examination (Study III)**

Orthopantomograph, apical or bite-wing radiographs were collected, if not available, only from patients who underwent prosthetic rehabilitation. Bite-wing or apical radiographs were taken when Try-in of the crown-copings was performed; after the cementation of the crowns to check for excess cement and, when indicated, in patients who developed dental problems following the prosthetic treatment.

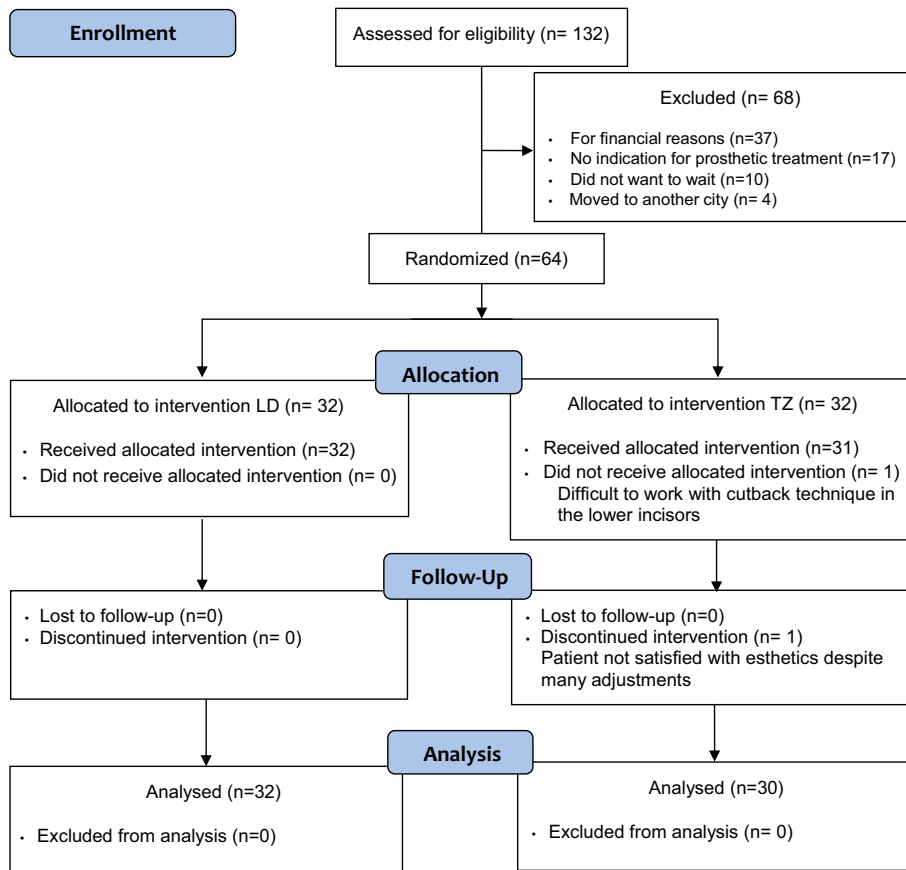
### **Registration, indication and blinded randomization (Study III)**

This study was registered at [www.controlled-trials.com](http://www.controlled-trials.com) (ISRCTN16324420). Prosthetic treatment was only indicated when at least one of the following criteria was fulfilled:

- unacceptable esthetic problems
- mechanical weakening of the teeth
- occlusion severely affected in an adverse fashion
- hypersensitivity that could not be relieved by other approaches

Upon enrollment, each participant received an ID number. Subsequently, a list generated by [www.randomization.com](http://www.randomization.com) was used to divide the participants randomly into two groups: the first to receive crowns made of lithium disilicate (LD) (IPS e.max-Press, Ivoclar Vivadent) and the second crowns made of translucent zirconia (TZ) (BruxZir 3Y-TZP zirconia

CAD/CAM, Glidewell Laboratories). WH, the only person who had access to the list, performed this randomization. In connection with the control examinations, neither the patients themselves nor the examiner knew the type of the crown material. All crowns were delivered between August 2013 and December 2018. 58 patients were treated by WH. For practical reasons, as well as to maintain the blinded randomization, the remaining 4 were treated by two calibrated dentists. Figure 10 presents a flowchart of the study protocol.



**Figure 10.** Flowchart illustrating the steps in the Random Control Trial

TZ= translucent zirconia (BruxZir, Glidewell), LD= lithium disilicate (IPS e. max Press, Ivoclar Vivadent)

### **The multidisciplinary approach (Study III)**

In some cases, specialists at other departments at Folk tandvården, St Erik's Hospital and Eastmaninstitutet, Stockholm, were consulted prior to beginning prosthetic treatment. Their role was to perform pre-prosthetic treatments, such as crown lengthening and endodontic and orthodontic treatment, when indicated. In addition, some of the participants received dental implants at the Department of Oral Surgery.

### **Prosthetic treatment (Study III)**

Prior to prosthetic rehabilitation, the sensitivity of the dental pulp was tested using ethyl chloride and/or electrical stimuli in order to assess its health. The schedule for prosthetic treatment of all participants was standardized.

*Step 1:* Each patient's study models was mounted in centric relation in a semi-adjustable articulator and a diagnostic wax-up created in accordance with appropriate occlusal-esthetic prescription. Soft PE tray splints (polyethylene, Erkodent) were constructed in a vacuum for later use in chair-side fabrication of temporary restorations. The vertical dimension was increased only when necessary to create enough space for the restorations required. In cases of localized TW, space for the prosthetic restoration was created utilizing the Dahl concept [80], by the use of temporary constructions; and/or adjustment of antagonising teeth (enameloplasty).

*Step 2:* To allow construction of the provisional restoration with the planned vertical occlusal dimension, all worn teeth in one arch were prepared during one single visit. A chamfer finishing line with a width of at least 1 mm was created and removal of tooth substance was kept to a minimum. While a stump height of at least 4.0 mm was ensured, irregularities in the stumps were retained to enhance mechanical retention.

In cases where bi-maxillary rehabilitation was indicated, in order to replicate as many details of the diagnostic wax-up created at the first step as possible, the opposing dental arch with the unprepared teeth was built up by a temporary composite material with the help of the soft vacuum-formed PE tray splints. Thereafter, bite registration was performed between

the prepared arch and the unprepared temporarily enhanced opposing arch. The material employed to register this bite was sent to the dental laboratory, along with an alginate impression of the opposing enhanced arch.

Temporary composite restorations for the prepared teeth were made chair-side by the use of the soft vacuum-formed PE tray splints and were cemented by eugenol-free temporary cement. At the end of the session, the temporary composite material used to build up the unprepared teeth was removed and laboratory fabricated provisional restorations for the prepared teeth were ordered for the following visit.

All necessary alterations were conducted on provisional restorations in order to avoid major adjustment of permanent restorations. For most of the participants, a second visit was required to refine the preparation of the teeth before taking the final conventional impressions.

*Third step:* Try-in of the crown-copings was performed and the crowns were assured to fit in occlusion and articulation movements. Minor adjustments were made chair-side and new bite registration was collected before sending the copings to the dental technician for coats of stain and ceramic glaze.

*Fourth step:* The ceramic crowns were cemented in place with 10-MDP-based self-etching adhesive cement (Panavia f 2.0, Kuraray). The same cementation protocol was employed for both LD and TZ crowns, with the exception that the inner surfaces of the LD crowns were etched with 4.5% hydrofluoric acid (IPS ceramic Etching Gel, Ivoclar Vivadent) for 20 sec at the dental laboratory. Static and dynamic occlusion were checked and minor corrections were required in only about 10 of the crowns, which were re-polished with ceramic silicone polishers.

### **Fabrication of the crowns (Study III)**

All crowns were constructed by the same 5 dental technicians working at the same laboratory. While all participants were given the opportunity to meet the dental technician at the laboratory to discuss esthetic features, the technicians were not allowed to reveal the type of the ceramic material used to make their crowns. Despite attempts to create and maintain a minimal material thickness of 1 mm, lack of space led

to some localized areas on the crowns being only 0.6 mm thick. While the majority of the TZ crowns were monolithic, 69 crowns were constructed with facial cutbacks. Moreover, in cases where it was difficult to achieve an acceptable color match, a number of crowns were provided with veneered porcelain.

### **Clinical evaluation of the crowns and follow-up (Study III)**

Baseline and follow-up evaluations of participants who received all-ceramic crowns were carried out between August 2013 and December 2019. In this connection all patients were questioned about their general status and possible postoperative complaints, as well as whether they had undergone any other kind of dental intervention. The clinical performance and success rate of the restorations were assessed by an independent, blinded observer on the basis of modified United States Public Health Service (USPHS) criteria [81]. Clinical photographs were taken both prior to the prosthetic management, at baseline and in connection with all follow-up visits.

### **Statistical methods**

In all cases statistical analyses were performed using the IBM SPSS (versions 21 and 22) and Microsoft Excel 2016 software.

#### **Study I**

Some details about the statistical method applied in this study are mentioned previously, please see: Special methodological approaches - Cluster analysis (Study I).

In comparing the two clusters, the Chi-Square and Fisher's exact tests were used for analysis of categorical variables and T-test for the continuous variables. Although a  $P$  value  $< 0.05$  was initially considered statistical significant, application of the Bonferroni correction to reduce the number of false-positives (type I error) [82] resulted in an adjusted significance level of  $P < 0.003$ . Cohen's kappa was used to assess intra-examiner reliability for two independent ratings of TW in 36 randomly selected patients.

## Study II

Clusters A and B were compared with respect to age, total number of maxillary and mandibular teeth, and the number of maxillary and mandibular teeth with TW > grade 2 utilizing simple t-tests. The Chi squared test was employed for the analysis of potential gender differences.

McNemar tests were employed to examine potential differences in the distribution of wear between three groups of maxillary and mandibular teeth, i.e., the anterior teeth (the central and lateral incisors and canines); the first and second premolars; and the first and second molars. Simple binary logistic regression models were applied to determine potential relationships between the presence of various morphological criteria in the two clusters. The average number of teeth per participant that exhibited the morphological criteria specified was compared using Mann-Whitney tests.

To assess the reliability of identifying the presence or absence of 10 morphological features, linear weighted Cohen's kappa was calculated as an indicator of intra- and inter-observer agreement. Moreover, intra- and inter-examiner reproducibility concerning the average number of teeth per patient identified with the morphological criteria specified were examined utilizing the intra-class correlation coefficient (ICC). A P value < 0.05 was considered statistically significant.

## Study III

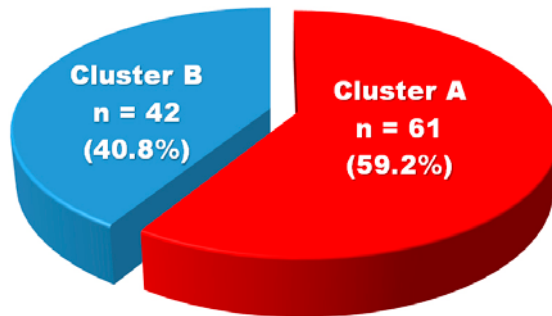
Absolute failure was defined as clinically unacceptable loss of a crown demanding replacement of the entire restoration. Relative failure was defined as the occurrence of endodontic complications and/or minimal ceramic fractures that were clinically tolerable, as well as loss of crown adhesion that could be successfully re-bonded. Comparison of the USPHS criteria concerning the two types of ceramic crowns under study, as well as the two clusters was performed with the Chi square test.

## RESULTS

### Study I

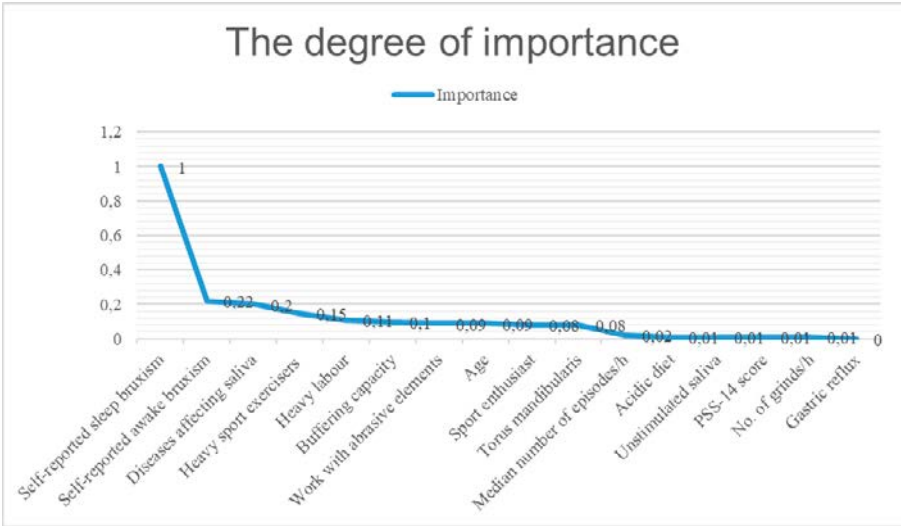
In total, 125 patients (29 women, 96 men) with a mean (SD) age of 43.1 years (10.2) were included in this study. Their mean (SD) number of teeth was 27.1 (1.3) and of teeth with TW > grade 2 was 15.9 (6.0). Intra-examiner reproducibility for the observer who re-rated TW in 36 randomly selected subjects was very good ( $K = 0.8-1.0/\text{tooth}$ ).

**Construction and quality of the clusters:** Of the 125 participants examined by unsupervised two-step clustering, variable selection and cluster discovery resulted in the exclusion of 22 from the final model, due to lack of data regarding the PSS scale or of salivary and/or EMG measurements. Thus, the final cluster model consisted of 103 individuals (80 men (77.7%), 23 women (22.3%)) and encompassed 16 variables; with 47 men (77%) and 14 women (23.0%) in cluster A (total  $n = 61$  or 59.2% of all participants) and 33 men (8.6%) and 9 women (21.4%) in cluster B (total  $n = 42$  or 40.8%) (Fig.11) with a A/B cluster size ratio of 1.45. A value of 0.2 for the Silhouette measure, which is an indicator of cohesion and separation, indicated that the cluster quality was fair. Overall, the clustering algorithm generated two relatively well-separated groups of clinical interest.



**Figure 11.** The cluster model constructed

**Comparison of the two clusters:** The most important regulator of the clustering was self-reported sleep bruxism, while the least important predictor was a history of gastric reflux and/or other conditions involving intrinsic acids (Fig. 12). Table 3 depicts the four major characteristics of the smaller cluster B, three of which were in fact mechanical risk factors, i.e., self-reported sleep ( $P\leq0.001$ ) and awake bruxism ( $P\leq0.001$ ) and heavy exercise ( $P=0.001$ ). The fourth factor was diseases affecting the saliva ( $P\leq0.001$ ). With respect to the other parameters examined, there were no statistically significant differences. It is worth mentioning that a high percentage of the participants in both clusters frequently consumed an acidic diet and exhibited torus mandibularis.



**Figure 12.** The degree of importance of the various predictors in connection with construction of the final cluster model, as indicated by the clustering algorithm



	Cluster A (n=61)	Cluster B (n= 42)	<i>P</i>
Self-reported sleep bruxism	1 (1.6%)	39 (92.9%)	$\leq 0.001^*$
Self-reported awake bruxism	28 (45.9%)	36 (85.7%)	$\leq 0.001^*$
Diseases affecting saliva (Asthma, diabetes, hypertension, diabetes mellitus)	8 (13.1%)	20 (47.6%)	$\leq 0.001^*$
Heavy sport exercisers (body builders)	1 (1.6%)	9 (21.4%)	$0.001^*$

**Table 3.** Variables with respect to which the two clusters differed significantly N (%) = number (percentage) of participants. \*Adjusted significant difference after Bonferroni correction of  $P < 0.003$

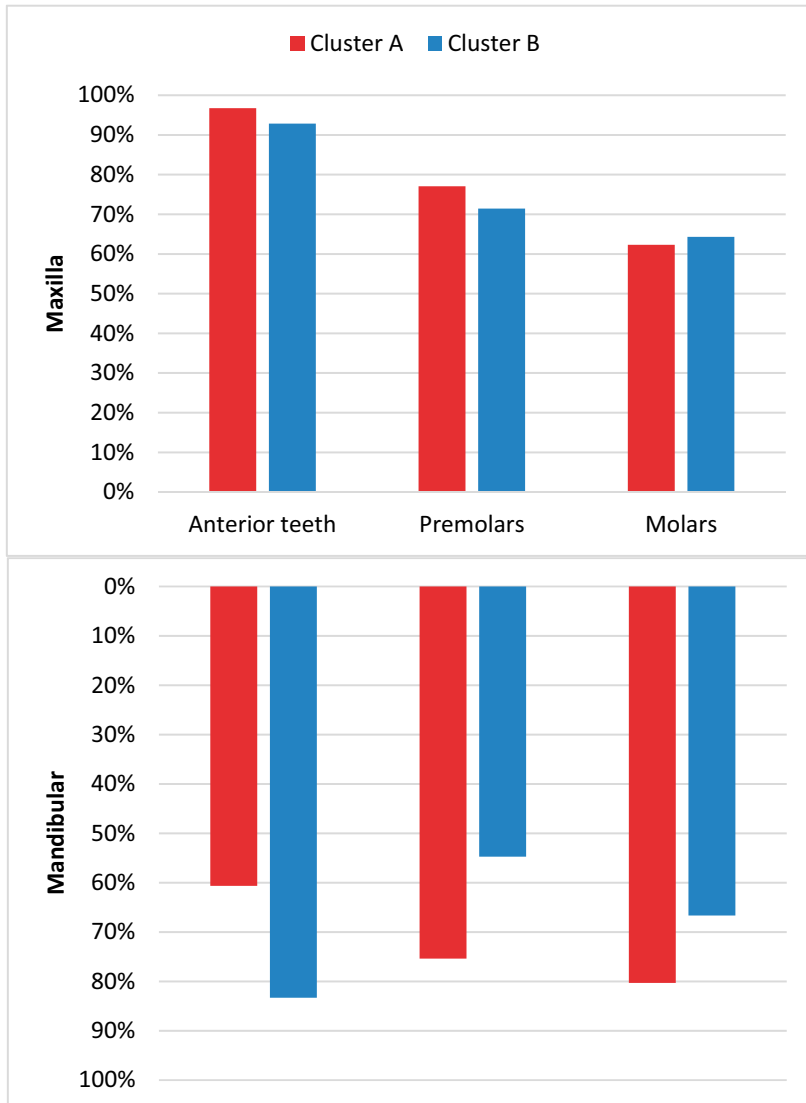
## Study II

103 of the patients (23 women (22.3%), 80 men (77.7%)) clustered into two subgroups in Study I also participated in Study II. Cluster A consisted of 61 patients (14 women (23.0%), 47 men (77.0%), mean age 43.1 years (range 14-65, SD 10.2)) and cluster B had 42 patients (9 women (21.4%), 33 men (78.6%) mean age 46.0 years (range 27-65, SD 9.7)). Thus, the participants allocated to cluster A were younger than those in cluster B ( $p = 0.015$ ).

**Comparison of the clusters with respect to the distribution of extensive TW:** Table 4 and figure 13 presents the distribution of extensive TW in the two clusters generated, in terms of the percentage of participants with TW > grade 2 and in relationship to three groups of maxillary and mandibular teeth. The participants in cluster A exhibited a higher percentage of extensive TW in the maxillary anterior teeth and mandibular molars in comparison to the corresponding opposing groups of teeth ( $P < 0.001$  and  $< 0.007$ , respectively). In contrast, the individuals belonging to cluster B demonstrated no significant differences between any of the three groups of opposing teeth.

Cluster	Teeth group	Upper	Lower	<i>P</i>
<b>A</b>	<b>Anterior teeth (CI+LI+C)</b>	96.7%	60.7%	<b>&lt;0.001*</b>
	<b>Premolars (1<sup>st</sup> P+2<sup>nd</sup> P)</b>	77.0%	75.4%	1.000
	<b>Molars (1<sup>st</sup> M+2<sup>nd</sup> M)</b>	62.3%	80.3%	<b>0.007*</b>
<b>B</b>	<b>Anterior teeth (CI+LI+C)</b>	92.9%	83.3%	0.219
	<b>Premolars (1<sup>st</sup> P+2<sup>nd</sup> P)</b>	71.4%	54.8%	0.092
	<b>Molars (1<sup>st</sup> M+2<sup>nd</sup> M)</b>	64.3%	66.7%	1.000

**Table 4.** Comparison of the percentages of extensive TW in three groups of teeth in clusters A and B. P-values refer to statistical comparisons between the upper and corresponding lower group of teeth. CI= central incisors, LI= lateral incisors, C=canine, P=premolars, M=molars



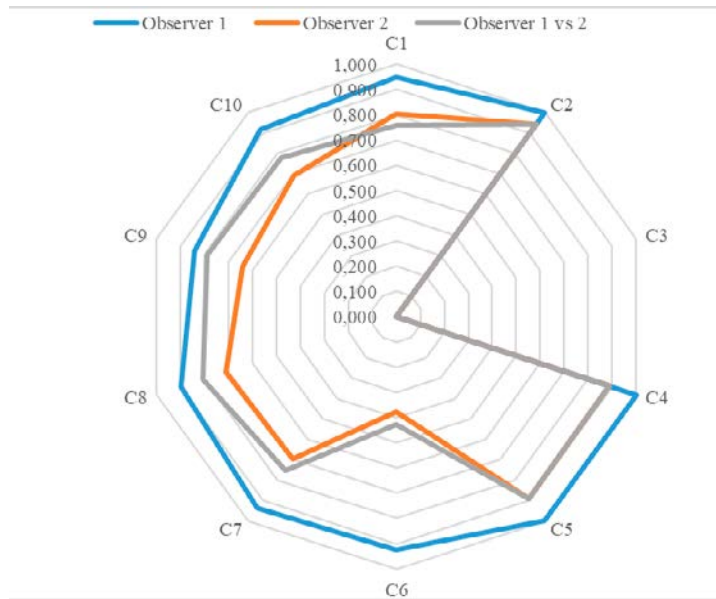
**Figure 13.** Distribution of extensive tooth wear. Percentage of individuals in cluster A and cluster B with TW > grade 2.

Anterior teeth=central incisors, lateral incisors and canines. Premolars=1<sup>st</sup> premolars and 2<sup>nd</sup> second premolars. Molars=1<sup>st</sup> molars and 2<sup>nd</sup> molars

**Comparison of the two clusters with respect to the presence of specified morphological features of TW:** The participants belonging to cluster A exhibited a higher prevalence of the morphological features 1, 2, 4 and 5, while cluster B had a higher prevalence of feature 8 (Fig. 9). Multiple binary logistic regression using stepwise variable selection revealed that the presence of feature 8 was the only difference between the two clusters that was statistically significant.

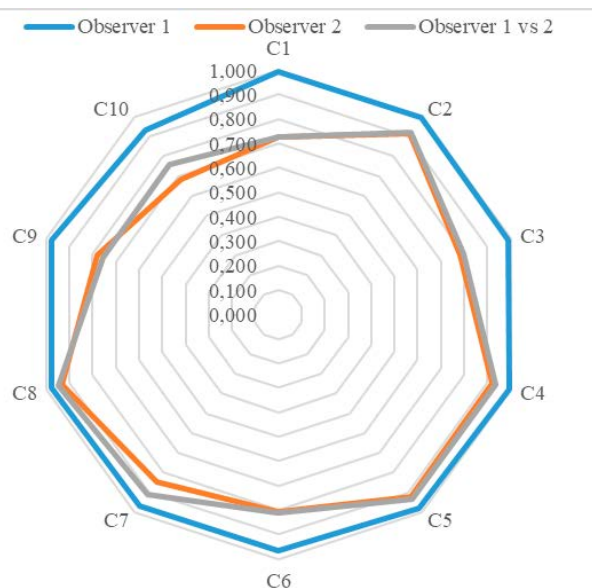
**Comparison of the two clusters with respect to the average number of teeth in each patient that exhibited these specified morphological features:** While the patients in cluster A had a higher number of teeth demonstrating feature 2, those in cluster B had more teeth displaying features 6 and 9 (Fig. 9).

**The reliability of identification of these morphological features:** Figure 14 illustrates the intra- and inter-observer agreement with respect to scoring of the presence of the 10 morphological characteristics specified. As can be seen, the intra-examiner kappa values for the first and second examiners were very good (0.84 - 1.00) and good to very good (0.64 - 0.94), respectively, with the exception of feature 6, for which these values were only fair (0.38). Consequently, the inter-examiner kappa values were good to very good (0.75- 0.94), again with the exception of feature 6 (0.46). Morphological feature 3 was present in all of the 41 individuals selected randomly to test reliability.



**Figure 14.** The intra- and inter-observer agreement concerning the presence or absence of specified morphological characteristics of TW, as indicated by linear weighted Cohen's kappa. No measure of association could be calculated for C3, since this feature was present in all of the 41 participants selected randomly for determination of these agreements.

The intra-class correlation coefficients (ICC) for intra- and inter-observer reproducibility regarding the average number of teeth per individual that demonstrated the specified morphological features are shown in Figure 15. These values for the first and second observers were excellent (0.99 - 0.93) and good to excellent (0.68 - 0.93), respectively. Consequently, the inter-examiner ICC values were good to excellent (0.72 - 0.93).



**Figure 15.** The intra- and inter- observer reproducibility concerning the average number of teeth per patient that exhibited the morphological criteria specified (C1-C10), as indicated by intra-class correlation coefficients (ICC).

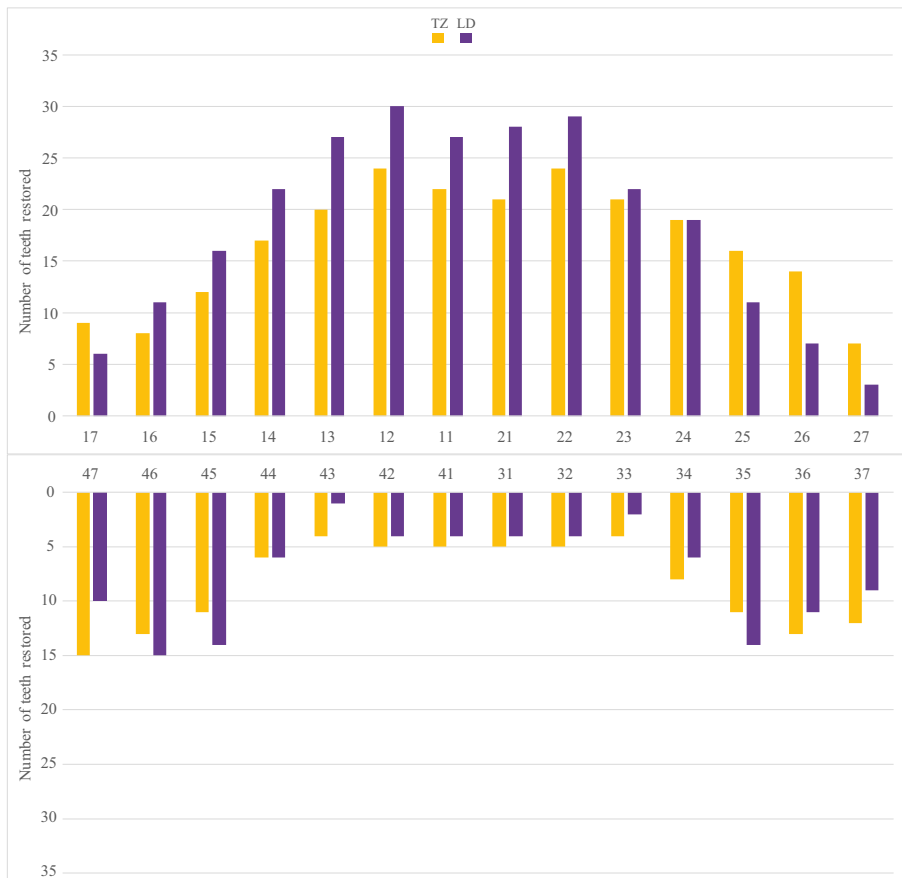
### Study III

This study included 64 patients [19 (29.7%) women and 45 (70.3%) men] with a mean age of 44.8 (range 25-63) years. The numbers of maxillary and mandibular teeth with TW > grade 2 were 627 (mean 9.8, SD 2.8, range 4-14) and 426 (mean 7.2, SD 4.1, range 0-14), respectively.

**The reason(s) for seeking treatment:** Each participants answered 4 questions regarding his/her reason(s) for seeking treatment and could choose more than one answer. Most patients wanted prosthetic management primarily for esthetic reasons (83.9%), followed by concern about the progression of wear (59.7%), hypersensitivity of the teeth (38.7%) and problems with chewing (24.2%).

**Dental status prior to prosthetic rehabilitation:** In total, 698 teeth had been restored with different types of fillings (composite resin, amalgam, GI, ZOE) and an additional 23 were fitted with all ceramic or metal-ceramic constructions (inlay, onlay, veneer or crown). Moreover, 32 teeth had root fillings and there were 7 remaining roots. Only one patient had a single implant.

**Inclusion/exclusion and analysis:** As shown in Figure 10, a total of 62 patients were analyzed (LD group=32, TZ group=30). Two women were excluded from the TZ group; the first because the small size of her lower incisors did not allow use of a cutback technique (she received LD crowns instead). The second woman was excluded because of high esthetic demands. In total, 713 crowns were inserted (LD= 362, TZ= 351). Figure 16 shows the distribution of the delivered maxillary and mandibular crowns in the study population.



**Figure 16.** The distribution of the delivered maxillary and mandibular crowns in the study population TZ= translucent zirconia (BruxZir, Glidwell), LD= lithium disilicate (IPS e. max Press, Ivoclar Vivadent)

**Modified USPHS ratings regarding the 2 types of the delivered all-ceramic crowns:** The outcome was assessed after mean follow-up periods of 14, 31, 39, 54 and 65 months. At present, all of the original participants are still engaged in the study and most have gone through the first recall (at 12-24 months). Since the crown restorations were performed over a period of > 5 years, some of the patients have not been involved long enough yet for subsequent recalls. Moreover, some participants could not take part in the follow-up visits as scheduled and instead did so later.

After monitoring for up to 6 years, the overall survival rate for both types of crowns was 99.7% (98.6% for LD and 99.1% for TZ). After one year there was loss of retention with one LD crown (the tooth received a new crown), and after three years one tooth with a TZ crown fractured at the cemento-enamel junction. Three patients in each group developed minimal ceramic fractures or apical lesions, or their crowns lost adhesion and had to be rebounded. Baseline assessment of color differed significantly: the LD crowns showed a better match (84.8% Alpha, 15.2% Bravo) than the TZ crowns (36.5% Alpha, 63.5% Bravo), including TZ crowns with veneered porcelain ( $P < 0.001$ ). No secondary caries or cracks were observed.

**Modified USPHS ratings regarding the 2 clusters:** Following the same follow-up period of up to 6 years, the survival rate of crowns was similar for both clusters; 99.8% for the chemical group (to which the patient whose crown had to be replaced belonged; see above) and 99.7% for the mechanical group (where one fracture at the cemento-enamel junction occurred; again, see above).

The success rate was 99.7% for both clusters. With the chemical crowns, three patients developed apical lesions in altogether 4 teeth, one developed a minimal ceramic fracture and another patient had two crowns which lost adhesion and had to be rebounded. Failure in the mechanical group was ascribed to cohesive fracture in one of the ceramic crowns.

At baseline, the marginal adaptation for the crowns in the chemical group was better (98.1% Alpha, 1.9% Bravo) than that of the crowns inserted in the mechanical group (94.9% Alpha, 5.1% Bravo) ( $p = 0.02$ ). Furthermore, at this same time-point, the anatomic form of the crowns



in the chemical group (91.4% Alpha, 8.6% Bravo) was significantly better than that of those in the mechanical cluster (56.8% Alpha, 43.2% Bravo) ( $p < 0.001$ ). In contrast, after one year (when most of the participants showed up for follow-up), the crowns in the mechanical group were significantly better in this respect (95.5% Alpha, 4.5% Bravo) than those in the chemical group (83.6% Alpha, 16.4% Bravo) ( $p < 0.001$ ).

**Additional prosthetic restorations:** In addition to the insertion of all-ceramic crowns in all patients, the following prosthetic restorations were also performed: 38 all-ceramic and two metal-ceramic crowns inserted onto non-vital teeth; 14 fixed dental prosthesis; 20 onlays and veneers; two gold posts; 30 single implants and three fixed implant prostheses. Excluding their wisdom teeth, the patients had a total of 823 restorations in occluding pairs of teeth (mean=13.3, SD=1.1, range=10-14).

## DISCUSSION

### Methodological considerations

The three studies described here illustrate the complexity of problems associated with extensive TW in adult patients. Unlike children and adolescents [83, 84], an adult patient has been exposed to a variety of potential risk factors for many years and the apparent multifactorial nature of his/her problem makes analysis difficult, both in theory and practice.

Among other things, we needed to establish a reliable and approved system for classification technique from the very beginning. We did not want to rely on systems proposed previously, since these were based on the presumed underlying risk factors or morphological characteristics [85-88]. The clustering analysis utilized here does not rely on predefined criteria, i.e., no information about any of the subjects is used to assign him/her to a cluster.

This is the first time that two-step cluster analysis has been used to explore possible variations in the features of TW. The algorithm employed creates clusters on the basis both categorical and numerical variables; is capable of analyzing large amounts of data efficiently; and does not require a control group. Other studies have taken only limited number of background factors into consideration [88-90], whereas we could analyze a much larger set of risk factors for TW and still interpret the results obtained in a relatively simple manner.

Our patients with TW were divided into two clusters, a larger A and smaller B cluster, on the basis of demographic and self-reported information; clinical findings; and salivary and EMG measurements. A higher percentage of the patients in cluster B had mechanical risk factors, including self-reported sleep and awake bruxism, heavy exercise, diseases that affect the saliva. In light of the multifactorial etiology of TW, it was not surprising that the two clusters shared many characteristics, mainly extensive consumption of an acidic diet and the presence of torus mandibularis.

Some of the methodical difficulties and limitations need to be addressed here. Cluster analysis is not reproducible; excluding the least important

predictor will not guarantee a better cluster quality or the same sequence of predictors in the next generated model. Furthermore, including many variables in clustering 125 patients may decrease the importance of certain variables. Fewer variables or larger study population may probably increase the chances of larger number of clusters with high internal homogeneity and/or increase the quality of the emerged cluster model. Additionally, it is important to remember that the cluster to which any individual is assigned might change as new risk factors (positive or negative) are encountered in the future. For this reason, when longitudinal studies based on cluster analysis are carried out, the case history and eventual risk factors for each patient should be kept up-to-date and continuously reconsidered.

### **The drawbacks of emphasizing erosion as the main risk factor for TW in adults**

In the current scientific literature, chemical factors such as dietary habits, reflux disease and eating disorders, along with the characteristics of saliva are considered to be the main causes of TW [78, 91]. This assumption might very well be misleading and will certainly influence the collection and dissemination of reliable information on TW, as well as the subsequent preventive and restorative treatment of worn dentition.

Unlike other investigations, a distinctive feature of the current project is that numerous presumed risk factors for TW, both chemical and mechanical, as well as factors affecting the saliva were included in the analysis. A high percentage of our participants had presumed mechanical risk factors like sleep and awake bruxism; heavy labour (builders, carpenters, truck drivers, military and police officers, farmers); and heavy exercise (body-builders). In addition, many of them used snuff and/or worked in dusty environments (e.g., electricians, carpenters, builders, road-workers, and rock-blasters).

Since a number of them had started using snuff and performing these jobs already as teenagers, it is possible that more of their TW lesions were due to abrasion and/or attrition than erosion, which might explain why TW is more prevalent among men than women. For this reason, the results of studies on TW which consider only chemical etiological factors

and salivary parameters should be interpreted with caution, especially with respect to adult patients. Future research will reveal whether the varying profiles of TW observed here are also present in other, preferably larger cohorts of individuals with TW.

### **Some morphological criteria might be helpful in identifying the relevant risk factors for individual patients**

Various morphological features of TW lesions have been described in the scientific literature, primarily on the basis of clinical observation alone. Here, we tested a number of these morphological characteristics in our clinical trial based on a study manual (Fig.8) with standardized clinical photographs. Furthermore, this investigation was important in terms of providing empirical support for the final cluster model.

The two phenotypes of TW observed differed with respect to the distribution and nature of morphological features, perhaps as a consequence of exposure to different risk factors. Intra and inter-examiner reliability in the identification of these features was good to very good. It appears that certain clinical features may be used to differentiate between individuals with different TW phenotypes:

- The most pronounced difference and beneficial criterion was having similar degree of occlusal/incisal TW that characterizes the mechanical cluster. In a similar manner, matching facets between two or more moving /functional surfaces may also be characteristic of adults with TW of mechanical etiology.
- The features characteristic of adults with TW presumed to be caused chemically might include thin and irregular incisal enamel with increased translucency; more extensive wear of the upper than the lower anterior teeth; loss of convexities on the palatal side of the maxillary teeth; and an intact palatal border of enamel along the gingival margin of the maxillary teeth.

On the other hand, two other features often recommended for the identification of patients with TW of chemical background – namely, concavities and cuppings on the occlusal surfaces of premolars and molars, as well as cervical/buccal lesions that are broader than they are deep – do

not seem appropriate, since most of our participants exhibited these features, regardless of background. Furthermore, use of margins of existing restorations on premolars and molars that are higher than the surrounding tooth structure as a criterion might also be questionable, since the inter-examiner kappa value for this feature was only fair.

Although few of our participants had some malposition or interference associated with localized wear of buccal and/or lingual surfaces, a number of them had a history of failed orthodontic therapy or of discussion of such therapy during childhood or as teenagers. Furthermore, a number of those patients who participated in our RCT had received orthodontic therapy prior to our prosthodontic treatment (Fig.17). In attempt to avoid extensive and expensive prosthetic treatments, it would be worthwhile to evaluate tooth surface loss and the benefits of preventive orthodontic treatment for such patients in longitudinal studies.



**Figure 17.** A 43-year-old man with extensive TW, mainly of the lower anterior teeth. Notice the overeruption and retroclination of the upper incisors and the growth of the alveolar process in the same direction (a). He works as a boat builder and had undergone several unsuccessful orthodontic treatments. The patient took part in our RCT and received pre-prosthetic orthodontic treatment before the prosthetic rehabilitation (b).

### **Important implications of the findings of our RCT**

Study III was a traditional randomized trial in which 64 participants were randomized into two groups, one of which received lithium disilicate crowns and the other translucent zirconia crowns. Since it might be of interest from a prosthodontic point of view to consider the patients whose TW was of either a more “chemical” or a more “mechanical” etiology separately, it was decided post-hoc to present the results in terms of

these two different clusters as well. To the best of our knowledge, this is the first long-term randomized clinical trials on translucent zirconia, as well as the only RCT comparing these two modern ceramic materials in this manner. In fact, we even included patients with parafunctions (e.g., bruxism, heavy labour and heavy exercise), who are usually excluded from such studies, thereby presenting these two all ceramic materials with an extra demanding challenge.

### **The use of dental ceramics in patients with extensive TW**

The limited tooth substance remaining in patients with extensive TW renders their prosthetic treatment challenging and makes the outcome unpredictable. Although a number of the ceramic restorations here were no more than 1 mm thick, with some areas even 0.6 mm in thickness, the percentages of success and survival were still very high. Since core bulk fracture did not occur, less invasive crown intervention can be achieved with high-strength ceramic materials held in place by adhesive resin cements.

This project was designed in 2011 with the intention of comparing clinical performance and longevity of two monolithic all ceramic materials, i.e., LD pressed crowns (IPS e.max-Press, Ivoclar Vivadent), introduced in 2000, and TZ CAD/CAM crowns (BruxZir 3Y-TZP zirconia, Glidewell Laboratories) that came on the market around 2010 as a new promising alternative to the traditional bi-layered zirconia [92]. On many occasions, our dental technicians found it difficult to obtain an acceptable color match with the TZ crowns. For this reason, the buccal and/or incisio-buccal surfaces of a number of TZ crowns, mainly those inserted onto the upper anterior teeth, were layered or veneered with porcelain. One patient assigned randomly to receive TZ crowns had small anterior lower teeth, which made the cutback technique impossible to apply. This patient was excluded and received LD crowns instead.

In any case, crowns made of both ceramic materials exhibited the same long-term success and clinical performance, with the exception that a blinded examiner rated the TZ crowns (even those layered or veneered with porcelain) as less esthetically appealing. However, since this difference was considered to be within acceptable clinical limits. Therefore,

we conclude that usage of high- strength and, at the same time, attractive restorations like TZ or LD crowns might be the right choice for patients with worn dentition.

### **Should the strategy for rehabilitation of patients with extensive TW depend on their etiological background?**

The difficulties involved in defining the study group might be one important explanation for the lack of long-term studies on restorative treatment of patients with extensive TW. In contrast to other such investigations, we included patients with presumed mechanical risk factors such as bruxism, heavy labour and heavy exercise in our RCT. Bruxism has been proposed to be a probable cause for early restoration fractures, so patients who report this condition are often excluded, especially when evaluating all-ceramic restorations [93-95].

Analysis of the two clusters with different profiles allowed us to compare the long-term performance and success rate of all-ceramic crowns in a randomized clinical trial. Our 6-year observation revealed that the key factor for long-term success, regardless of etiology, is the use of adhesively luted high-strength ceramic crown materials. Consequently, patients with chemical or mechanical risk factors may be treated in a similar manner

Nonetheless, it is worth to mention that our results at baseline showed a significant differences between the two clusters with respect to the marginal adaptation and anatomic form of the crowns ( $P=0.02$  and  $p<0.001$  respectively). This difference may reflect the fact that in the case of the mechanical cluster, the crowns were relatively bulky, with wide occluding surfaces, in accordance with the recommendations of the well-known Swedish prosthodontist, Henry Beyron (1909-1992) [96]. According to Beyron, such a design provides a “harmonic function” by creating an axial load during both occlusion and sliding, thereby guarantying stable occlusion and interference-free sliding movements [96]. This difference between the clusters was unintended and it is not possible to evaluate the impact of this design on the results obtained. However, such a design might nonetheless provide a “dental guard” both day and night.

## **Obstacles and unanswered questions regarding the rehabilitation of worn dentition**

It has been proposed that whenever possible, a reversible, adhesive, additive strategy should be adopted when rehabilitating worn dentitions [97]. We do not advocate the prosthetic treatment described here for first-line management of TW, since it may, unfortunately, impose a lifelong need for maintenance on the patient, in addition to being highly invasive. Complications that may arise after the prosthetic treatment might not be due to this treatment alone, but also to other dental interventions, such as orthodontics, endodontics and oral surgery. Since our patients had extensive TW (1089 teeth) and/or heavily restored dentition (~721 teeth); long experience of failed restorations; and an expressed desire for restorations with better performance and esthetics, crown therapy was considered to be an appropriate choice.

An interesting observation made in connection with the follow-up visits and documented by the clinical photographs was that few of our patients developed spacing between the crowns inserted (Fig.18). Such spacing can arise as a result of the alterations in vertical dimensions and occlusal relationships between the dental arches associated with such rehabilitation. Of the four major factors responsible for dental balance – i.e., the intrinsic forces of the lips, cheeks, and tongue; the extrinsic forces associated with oral habits or orthodontic appliances; the forces of the periodontal membrane; and the forces of dental occlusion [98] -- the periodontal forces and resting positions of the tongue and lips are considered most important, since these are of long duration [98].

In a previous study, one group of participants with anterior open bite; received orthodontic treatment only, while another, similar group also received orofacial myofunctional therapy designed to exercise the muscles and modify orofacial functions . Occlusion was found to recur more often in those who received orthodontic treatment only [99]. The finding indicated that when the position is changed, the function will also alter, yet; the modification of the former will not necessarily lead to the efficacy of the latter. In addition to the protection against bruxism and wear of antagonist, teeth position changes following the prosthetic rehabilitation might be a further indication that justifies the use of night guard in these patients.



In connection with assessment of the long-term success of various prosthetic materials and constructions, occlusion, the number of occlusal contacts, occlusal forces, and wear on the enamel and/or material should all be taken into consideration [100-102] (Fig.19). Since new materials designed for this purpose continuously appear on the market, while others disappear, long-term clinical studies on these materials are essential, especially since dental authorities and organizations do not have any specific policies or requirements in this respect.



Figure 18. A 32-year-old woman with a history of adolescent anorexia nervosa, assigned to the chemical cluster. She had extensive TW, mostly in the upper arch, including a deep bite and spacing between the upper teeth (a. 1-5). She lost her first mandibular molars several years ago, most probably due to her extensive TW. This patient received lithium disilicate crowns on teeth 16-25 and 37 (b.1-5 depict clinical photographs taken at baseline) and subsequently developed spacing again between teeth 14-13 and 21-22 (c.1-5 show clinical photographs taken 51 months after restoration). She never used her night guard.

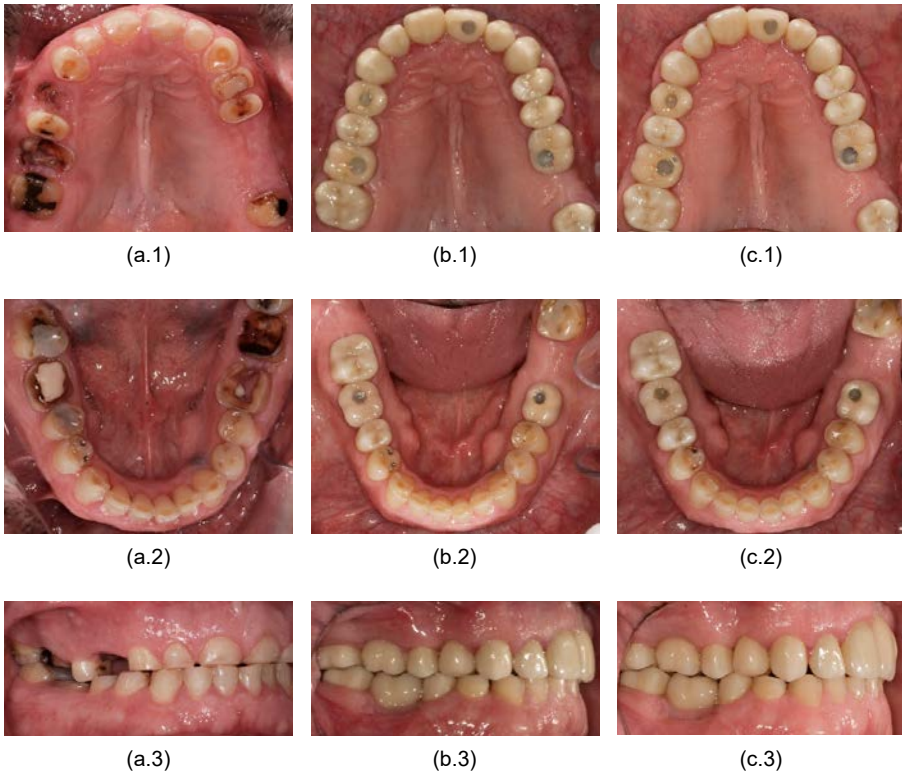


Figure 19. A 47-year-old man with extensive generalized TW (a.1-3), a history of stress, and self-reported awake and sleep bruxism, allocated to the mechanical cluster. He is used to carrying heavy objects, works in a dusty environment, is a body-builder and has motocross as a hobby. He had a bad experience with composite restorations and had no desire to restore his lower anterior teeth. He received monolithic TZ crowns on teeth 17, 15, 13-11, 22-25, 45, 47 and single implants at 16, 14, 21, 26, 36 and 46 (b.1-3 depicts clinical photographs taken in connection with the one-year follow-up). Three years after this prosthetic rehabilitation, he developed depression and high blood pressure and started taking lithium and antihypertensive medication. With time, the lower anterior teeth and veneered porcelain on the single implants developed signs of wear (C1-3). He does not use his night guard regularly



## ETHICAL REFLECTIONS

### **Informed consent**

Each potential participant both received written information and attended a presentation, in clear and simple language of every aspect of the project and its importance for improving our knowledge about TW. After this presentation, they were asked to confirm that they understood the information presented and thereafter to sign the consent form. All investigations and treatments for each patient were scheduled after he/she had agreed to participate.

### **Do-no-harm**

The commercial, single-channel, battery-operated and portable EMG device used to measure SB was developed in accordance with the relevant rules concerning patient safety.

In order to avoid metal allergy and provide the patients with restorations that were both durable and esthetically appealing, we employed high-strength all-ceramic monolithic materials in our randomized controlled trial. Although not allowed to discuss the type of ceramic material to be utilized for their restoration, each patient was able to discuss their desires concerning the color and form of the prosthetic crowns. Whenever it was difficult to achieve an acceptable color match with the translucent zirconia, the dental technicians were allowed to perform veneering with porcelain.

### **Voluntarism**

Each participant was treated in accordance with the Declaration of Helsinki and had the right to withdraw from the study at any time without having to give a reason.



## MAIN FINDINGS AND CONCLUSIONS

### Study I

On the basis of demographic and self-reported information, salivary and EMG measurements, and clinical findings, patients with extensive TW can be clustered into at least two groups whose members had been exposed to either presumed chemical or mechanical risk factors and exhibited different phenotypic characteristics. The most pronounced differences between these two clusters were the percentage and prevalence of presumed mechanical risk factors (sleep and awake bruxism, heavy exercise) and of diseases that affect saliva. With respect to all other presumed risk factors for TW, there were no significant differences between the two clusters. This approach can form the basis for a new system for classifying patients with TW, thereby helping to plan individualized treatment. Our hypothesis that there are different phenotypes among TW patients which can be distinguished based on comprehensive datasets including self-reports, clinical findings, EMG data and salivary characteristics was supported.

### Study II

The two groups of patients with TW identified by cluster analysis, differed with respect to the morphological characteristics and distribution of their wear lesions in a manner that suggests more pronounced exposure to presumed mechanical risk factors for one group and a more chemical background for the other. Although there was a certain degree of overlap between the two clusters in this context, these findings support the conclusion that the cluster model selected was clinically relevant and may allow differentiation between individuals with TW of different etiologies. The most definitive criterion for such differentiation is the presence of a similar degree of occlusal/incisal wear in both arches. The null hypothesis that the clinical presentation of the worn dentition in two phenotypes of TW patients did not differ in terms of distribution and morphology of wear lesions, was rejected.

### **Study III**

Observation in randomized clinical trial for as long as 6 years revealed that the key determinant of the long-term success of all-ceramic crowns in patients with extensively worn dentition, regardless of etiology, was the use of high-strength ceramic materials that were adhesively luted. Although a clinician who was unaware of which material the crowns were made of rated those composed of TZ as less esthetically pleasing than LD crowns, these two types of crowns did not differ with regard to long-term success and clinical performance. In light of the limited space and remaining tooth tissue in patients with extensive TW, less invasive crown intervention with such adhesively luted materials can be beneficial. The null hypothesis that there would be no differences between the two types of all-ceramic materials was partially supported. Whereas the second hypotheses; the long-term clinical outcome for patients with mechanical risk factors is worse than for those with chemical risk factors, was rejected.



## CLINICAL IMPLICATIONS

This research addresses important issues concerning TW, both regarding basic scientific knowledge and clinical applications.

- Ours is the first reported use of data mining and modelling of complex datasets to classify patients with extensive TW. The classifications provided by such cluster analysis may provide a valuable tool in connection with individualized treatment and/or prognosis.
- To our knowledge, our case control trial is the first in which the morphological criteria for TW in adult patients were evaluated on the basis of a manual constructed specifically for this purpose. The intra- and inter-examiner reliability of this approach were good to very good.
- Our assessment of the long-term performance of two types of modern ceramic materials for rehabilitation of extremely worn dentition in a RCT provides evidence on which to base the prosthetic management of patients with extensive TW, including those with presumed mechanical risk factors such as bruxism.
- The clinical relevance of cluster analysis was demonstrated by the formation of two clinically different clusters. This approach could potentially be applied to a great variety of large and complex clinical datasets.

## FUTURE PERSPECTIVES

- Assessment of the quality of life of patients with extensive TW and the impact of the prosthetic management on this quality. All patients included in the RCT have already completed a questionnaire that focuses on oral health-related quality of life (OHRQoL) (OHIP-14), both before and after the prosthetic treatment, as well as in connection with follow-up visits. This questionnaire addresses the four dimensions of orofacial pain, oral function, orofacial appearance, and psychological impact.
- Assessment of the impact of dentofacial appearance, which is becoming increasingly important in modern society. All of our patients who received prosthetic treatment also completed the orofacial esthetic scale (OAS), again both before and after the rehabilitation, as well as in connection with the follow-up visits. This one-dimensional instrument consists of 8-items designed to examine self-reported perception of one's own orofacial appearance. We will compare these perceptions with oral health-related quality of life. It will also be of interest to compare these perceptions with the assessment of our clinical examiners (based on USPHS criteria) regarding the esthetic appearance of the ceramic restorations inserted.
- Evaluation of the extent to which the costs for rehabilitation of worn dentition are covered by the state, insurance companies and/or the patients themselves. In addition, how much of these costs are related to the time required for treatment, follow-up, documentation and administration. Such information should help in planning the financial aspects of this type of healthcare.
- Construction of a standardized questionnaire concerning background risk factors and the clinical characteristics of wear lesions, with subsequent risk assessment, that can help clinicians design appropriate therapy for patients with TW. Such a questionnaire could be based on the questionnaires and forms used in the research described here, as well as on our present findings and a systematic review of the relevant scientific literature. The

usefulness of such form can be evaluated in a multicenter study with the involvement of artificial intelligence.

- Long-term evaluation of the performance of root-filled teeth supported with ceramic crowns, in addition to other delivered prosthetic constructions which have not been presented in our RCT.
- Even longer-term follow-up (for at least 10 years) of the performance of different types of all-ceramic crowns.

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From left: Peter Svensson, DDS, PhD, Professor, Aarhus university; Anette Jerner, research assistant, Folktandvården Eastmaninstitutet; Karl Wahlin, Senior Biostatistician; Wedad Hammoudi, DDS, Folktandvården Eastman institutet and PhD-student at Karolinska Institutet; Jan-Ivan Smedberg, DDS, PhD, Associate Professor, Folktandvården Eastmaninstitutet; Mats Trulsson, DDS, PhD, Professor, Karolinska Institutet



## MY STORY WITH THE PHD

Once upon a time on Friday 11<sup>th</sup> of December 2009, I asked my boss, Associate professor Jan-Ivan Smedberg, if he could support me in getting a PhD degree. He was very happy that day because his current PhD student Lars Hjalmarsson disputed at the same day. Without any hesitation I got a positive response. He told me that he and Associate professor Lars-Eric Moberg had always wished to find an answer concerning the prosthetic rehabilitation of patients with bruxism; how can we detect those patients and how should we treat them? After discussions with professor Mats Trulsson and Stress Research Institute, I wrote down a project regarding patients with bruxism which turned out to be extremely expensive. We modified the project to include patients with tooth wear and our hope was to identify patients with mechanical background factors and to solve the puzzle regarding their prosthetic management. At 2012, I became a PhD student at Karolinska Institutet and started my journey with tooth wear.

I had the opportunity to meet my big idol who wrote a lot about tooth wear; Professor emeritus Gunnar E Carlsson, and asked him for advice. He recommended me to perform a study about the prosthetic management of patients with tooth wear. I am happy that I succeeded in performing such a study. Time went so fast, I/we had planned and started with other studies that we could not finish: evaluate the role of occlusion in tooth wear by a digital occlusal analysis system and evaluation of biting and chewing behavior in patients with tooth wear. I really hope to finish those things and other projects in the future.

I can tell you that I always listened to Frank Sinatra- My Way and dreamt about the day I will face the final curtain and finish my thesis. Something that I never imagined is writing my thesis during the horrible Corona pandemic. In case you find anything wrong in this thesis, you can be rest assured that it is due to the nasty pandemic!

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